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Volume 1. Final Report

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ASSESSMENT OF FLUIDIZED-BED COMBUSTION SOLID WASTES FOR LAND DISPOSAL

Volume 1. Final Report

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Combustion	Earth Fills		21B	13C
Fluidized Bed	Linings			11G
Processing	Sorbents		13H	
Coal			21D	

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Abstract

The report, including 10 appendices, gives results of: (1) an analysis of representative samples of fluidized-bed combustion (FBC) wastes, (2) an assessment of the characteristics of leachates generated from the wastes under laboratory and field (landfill) conditions, (3) a characterization of the attenuation of the leachates by earth materials that are typical of disposal settings, (4) development of a way to predict the leachate generation behavior of FBC wastes under landfill conditions on the basis of laboratory test results by establishing a rigorous statistical relationship between the laboratory and field leaching results, and (5) assessment of the compatibility of commonly used landfill liner materials with FBC waste leachates. FBC is an emerging energy technology that holds promise for both high efficiency of energy conversion and minimization of adverse air quality impacts. A major advantage of FBC is that high-sulfur coal can be burned without the use of flue gas desulfurization equipment to meet air quality standards. The solid residues that are generated in an FBC unit are usually larger in volume and have different properties than the typical bottom ash from a conventional boiler.

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1.0 SUMMARY AND CONCLUSIONS

Fluidized bed combustion (FBC) is an emerging energy technology that holds promise both for high efficiency of energy conversion and for minimization of adverse air quality impacts. A major advantage of FBC is that high-sulfur coal can be burned without the use of flue-gas desulfurization equipment to meet air quality standards. During combustion in a fluidized bed, sulfur in the coal is oxidized to sulfur oxides as in conventional boilers, but these oxides then react with a sorbent that is injected into the fluidized bed with the coal. During steady state conditions, the sorbent constitutes more than 95% of the bed material. The sorbent, typically lime, limestone, or dolomite, usually forms calcium sulfate compounds, such as anhydrite, when the reactions with the sulfur oxides occur. The solid residues that are generated in an FBC unit are usually larger in volume and have different properties than the typical bottom ash from a conventional boiler. Because of the large volumes and potential environmental implications of FBC solid wastes, the Environmental Protection Agency (EPA) has undertaken a number of investigations of their disposal properties. This report constitutes an integral part of the EPA program of investigation.

The objectives of this investigation were to obtain and analyze representative samples of FBC wastes, assess the characteristics of leachates generated from the wastes under laboratory and field (landfill) conditions, and characterize the attenuation of the leachates by earth materials that are typical of disposal settings. An attempt was made to develop a means of predicting the leachate generation behavior of FBC wastes under landfill conditions on the basis of laboratory test results by establishing a rigorous statistical relationship between the laboratory and field leaching results. In addition, an assessment was made of the compatibility of commonly used landfill liner materials with FBC waste leachates. The lab studies were performed at Radian Corporation laboratories in Austin, Texas, and the field investigation took place at the former EPA Mine Drainage Control facility, which is located about nine miles south of Morgantown, West Virginia.

1.1 Sources of Samples

Sources of FBC wastes were selected to be as representative of future FBC waste streams as possible while at the same time being capable of providing a sufficient quantity of sample for laboratory and field experiments. The waste source selected for pressurized FBC (PFBC) was the Exxon Miniplant at Linden, New Jersey. Two atmospheric FBC (AFBC) sources were selected — the EPRI/B&W unit at Alliance, Ohio and the Georgetown University boiler in Washington, D.C. Both AFBC units were operating in the recycle mode when wastes were collected. The three wastes obtained were designated the Exxon PFBC, Alliance AFBC, and Georgetown AFBC wastes.

Several types of geological substrate materials (termed "disposal media" here) were obtained from the vicinity of the field cells in northern West Virginia and eastern Ohio. They were selected as representative of substrate materials at future disposal sites in the eastern U.S. and included shale, coal mine interburden, sandstone, glacial till, alluvium, and limestone. These samples were used in the lab and field studies to investigate the interaction (attenuation and mobilization) of FBC waste leachate with typical substrate materials.

1.2 Overview of Procedures

The program included extensive studies both in the laboratory and in the field. The principal component of the lab investigation was a six-step sequential batch equilibration protocol for assessing the characteristics of leachate after generation from FBC wastes and after exposure to samples of the disposal media. The leaching steps of the batch equilibration protocol consisted of initial leaching of the waste (at a liquid-to-solid ratio of

10:1) with deionized water, secondary leaching of leached waste with additional deionized water (in Step 2) for up to seven repetitions; and secondary exposure, sequentially for up to seven repetitions, of leachate to fresh waste in Step 3. These steps were designed to evaluate initial leaching of waste in a landfill, secondary leaching of waste as it continues to be leached by additional infiltrating precipitation, and the ability of leachate, once generated, to continue to take up contaminants as it is exposed to additional waste.

The leachate was exposed to the disposal media in order to assess the tendency of contaminants to be attenuated by (or mobilized from) the media. Step 4 of protocol was intended to assess the initial attenuation of leachate from Step 1 when exposed to a sample of disposal medium. Step 5 was designed to evaluate the ability of a disposal medium sample to continue to attenuate fresh leachate from Step 1. In Step 6, the leachate from Step 4 was repeatedly exposed to new samples of disposal medium to evaluate the progressive attenuation of the leachate by exposure to fresh media. Step 5 was repeated up to nine times and Step 6 was repeated five times.

Samples of the FBC waste and disposal media were analyzed in the lab for a variety of parameters. Physical properties that were determined included grain size distribution, specific surface area, and particle surface characteristics. The solids composition was investigated by X-ray diffraction to determine the crystalline phases present and by sample digestion and analysis to determine the chemical composition.

The laboratory studies also included two sets of leaching columns, one set containing disposal media only and another set containing layers of waste and disposal media. In addition, the FBC waste samples were subjected to the Extraction Procedure test for hazardousness (toxicity category) as set forth in regulations developed pursuant to the Resource Conservation and Recovery Act. Another component of the lab studies was the assessment of the compatibility of various landfill liner materials with FBC waste leachate.

The main feature of the field investigation was the design, installation, and operation of several large (four-foot diameter, seven-foot long) cylindrical field cells. Field cells containing Exxon PFBC and Alliance AFBC waste were constructed and operated below ground surface. These field cells, although hydrologically isolated from the local environment, were intended to simulate actual landfill conditions in the field as closely as practicable. The cells contained layers of waste and disposal media arranged similarly to a landfill configuration, with an upper layer of disposal medium to simulate landfill cover material, a layer of waste, and a lower layer of medium to simulate landfill substrate. Leachate sampling points were included at the base of the waste layer (upper sample point) for collection of unattenuated leachate and at the base of the lower layer of disposal medium (lower sample point) for collection of attenuated leachate. Several of the field cells were cored at the conclusion of the leachate sampling program, and the waste cores were analyzed for most of the same physical and chemical properties as the unleached waste.

The field studies also included two large-diameter permeameters containing FBC wastes. These permeameters were used to determine the permeability of uncompacted waste initially after emplacement and again after several months of exposure to weathering processes and chemical changes in the wastes.

1.3 FBC Waste Composition and Physical Properties

The principal crystalline phases found in the unleached Exxon PFBC waste were anhydrite, periclase, and quartz. The most significant compounds found in the solids analysis were calcium (22%), magnesium (12%), and sulfate (23%). After leaching in Steps 1 and 2 of the batch equilibration protocol, the most important minerals were gypsum, brucite, calcite, and quartz. Field cell leaching produced similar crystalline materials but with the addition of ettringite. The solids composition of both the lab- and field-leached PFBC waste showed a reduction in calcium, sulfate, and magnesium. The leached waste from the lab protocol had 12% calcium, 20% sulfate, and 8% magnesium. The field-leached waste contained 14% calcium, 18%

sulfate, and 8% magnesium. Both the crystalline and chemical composition data indicated the addition of water to the minerals during leaching.

Both the unleached and leached (Protocol Steps 1 and 2) Alliance AFBC waste contained quartz, calcite, portlandite, and hematite. The unleached and leached waste differed in that the unleached waste had anhydrite and lime whereas the protocol-leached waste had gypsum and ettringite. The leached waste from the field cells had the same crystalline composition as the protocol-leached waste. Unleached Alliance waste had 31-35% calcium and 10-13% sulfate. Lab leaching resulted in a reduction of the calcium content to 20-21% and of sulfate to 1.4%. Field cell leaching lowered the calcium to 21-24%, but sulfate remained at 11%. These results again indicate a hydration of minerals during the leaching process.

X-ray diffraction analysis of the unleached Georgetown AFBC waste revealed the presence of portlandite, anhydrite, quartz, calcite, lime, and hematite. Leaching in the laboratory protocol (Steps 1 and 2) resulted in the addition of ettringite and gypsum and the hydration of lime. Before leaching, the Georgetown waste was composed of 38% calcium and 8.5% sulfate. Lab protocol leaching reduced the calcium to 15-23%, and the sulfate content was about 7%.

Scanning electron micrographs were obtained for each of the three wastes in both the unleached and leached condition. The unleached Exxon PFBC waste consisted of irregularly shaped particles covered with fine material. A few spherical particles were also present. The leached PFBC waste also consisted mostly of irregular particles, but it contained in addition lath-shaped crystals which were probably precipitated calcite or a hydration product of calcium sulfate, possibly gypsum.

The unleached Alliance AFBC waste was also found to consist mostly of irregular particles and a few spheres. The leached waste consisted of generally smaller particles than the unleached waste and contained laths similar to those observed in the PFBC waste. Unleached Gerogetown AFBC waste contained two different groups of particle sizes, one from the beddraw and one from the fly ash component of the waste. The leached waste contained little of the original fine fraction, but had small needles adhering to the coarser grains.

Mixed (composite) samples of Exxon PFBC, Alliance AFBC, and Georgetown AFBC wastes were dry-seived to determine the particle size distribution of the "as-received" wastes. The mean grain sizes of these wastes were found to be 195 microns for the Exxon waste, 270 microns for the Alliance waste, and 230 microns for the Georgetown waste. The grain size distributions were quite similar for the Exxon and Alliance waste, although the Exxon waste was consistently finer grained. The Georgetown waste had a different grain size distribution than the other two wastes in that there was a higher percentage of material in the range below 100 microns.

The specific gravities of the Exxon PFBC, Alliance AFBC, and Georgetown AFBC wastes (after sample grinding) were determined to be 2.49, 2.65, and 2.42, respectively. The apparent bulk densities (after sample grinding) were 1.10, 1.29, and 1.21 g/cc, respectively. The specific surface area was obtained for the ground Exxon PFBC waste and was found to be 0.9 m^2/g.

The field permeability of Alliance AFBC and Georgetown AFBC waste was determined by constructing large (four-foot diameter and four-foot long) cylindrical permeameters at the field site. These permeameters were constructed above ground separate from the field cells. The waste was emplaced in the cells without compaction. The permeability of the waste was determined initially, at an interim point in the program, and at the conclusion of the field studies. The Alliance AFBC permeameter was operated about 19 months, and the Georgetown AFBC permeameter was in place for about 13 months. Data are given here for the initial permeability and the permeability after comparable periods of operation.

The initial permeabilities of the two wastes were quite similar, with 1.1×10^{-3} cm/sec for the Alliance AFBC waste and 1.7×10^{-3} cm/sec for the Georgetown AFBC waste. These initial permeabilities are within the range expected for a sandy loam soil. After 15.5 months of operation, the permeability of the Alliance AFBC waste decreased to 1.1 x 10^{-4} cm/sec. The permeability of the Georgetown waste decreased to 1.7 x 10^{-5} cm/sec after 13 months of operation. These permeabilities are comparable to a silty clay soil.

1.4 Leaching Properties of FBC Wastes

The leaching properties of the FBC wastes were evaluated in the laboratory sequential batch equilibration protocol (first three steps), in laboratory leaching columns, and in the large field cells. The Exxon PFBC and Alliance AFBC waste were investigated in all three sets of studies; the Georgetown AFBC waste was evaluated in the batch equilibration protocol. All three wastes were also subjected to the Extraction Procedure (EP) toxicity test set forth in regulations developed pursuant to the Resource Conservation and Recovery Act of 1976 (RCRA). The concentrations reported below are mean values from analysis of aliquots from several repetitions of the protocol steps and sample replicates.

1.4.1 Exxon PFBC Waste Leachate Composition

Step 1 leaching of Exxon PFBC waste for seven days produced leachates that had calcium and sulfate in the highest concentrations. The pH of the leachate was very high at about 12. The calcium concentration was about 1670 mg/L, and the sulfate concentration was about 1600 mg/L. Also present in relatively high concentrations were potassium (250 mg/L), sodium (17 mg/L), and boron (11 mg/L). Other significant species were Cl (4 mg/L), Sr (2.8 mg/L), Mo (2.5 mg/L), Mg (1.4 mg/L), and Si (1.3 mg/L)*. Other species were present in concentrations less than 1 mg/L. Comparison of the mass of each of the major species leached to the mass in the bulk solids of the PFBC waste showed that chloride was as much as 26% leached, boron was 20% removed, strontium about 13%, calcium about 7%, sodium about 5%, and sulfate about 6%.

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*Where chemical data are presented in the text of this report, the chemical species are generally spelled out when presented in sets of three or fewer. Symbols are usually used in sets of four or more.

Repeated leaching of the Exxon PFBC waste in Step 2 of the protocol resulted in constant or decreasing concentrations of all species except silicon and aluminum, which showed an increase. Repetition of Step 3, where the same leachate was exposed to fresh waste, resulted in increasing concentration trends. Only aluminum, iron, and silicon showed a decrease, and magnesium remained constant.

Three small, three-inch diameter leaching columns containing layers of Exxon PFBC waste and disposal media were used to evaluate the characteristics of leachate generated under laboratory column conditions. Two of the columns contained an upper layer of shale (to simulate natural cover material) and a lower layer of PFBC waste. The third column also contained these two layers and had in addition a lower layer of shale below the waste to simulate the substrate below a landfill. Leachate was collected from the bottom of all three columns, so the composition of the leachate reflected the combined effect of exposure to the layers of shale and PFBC waste.

The two columns without the lower layer of shale yielded leachates that again had calcium and sulfate as the most concentrated species, with concentration as high as 1000 mg/L for calcium and 3000 mg/L for sulfate. The pH was also again very high (11-12). Potassium and chloride ranged as high as 3500 mg/L and 410 mg/L, respectively. The total dissolved solids (TDS) reached 8500 mg/L. Boron was as high as 25 mg/L, lithium reached 4 mg/L, and molybdenum was as high as 2.8 mg/L. Aluminum and barium reached 1.7 and 1.2 mg/L, respectively. The leachates from the third column are described in a subsequent section describing attenuation of FBC waste leachate.

The leaching behavior of Exxon PFBC waste under field (landfill) conditions was evaluated by collection and analysis of leachates from the upper sample point of the field cells. This leachate reflected the combined effects of exposure of infiltrating precipitation to an upper layer of disposal medium (to simulate landfill cover material) and an 18 inch layer of PFBC waste. Two of the six PFBC field cells had shale in the upper layer, and the remaining four cells had glacial till, alluvium, limestone, and sandstone. The cells were operated for about 2 1/4 years, with a six-month period during which they were covered and not operated. A total of 30 leachate sampling events occurred during this period.

In general, many of the species in the upper sample point leachates had high concentration in the initial samples, but the concentrations showed considerable fluctuation. After the first month of sampling, during which several samples were taken, the concentrations oscillated much less, and smoother trends were observed. The concentration ranges in leachates from the latter part of the period of operation, when concentrations were more stable, were highest for sulfate and TDS (generally in the 1000 to 10,000 mg/L range), calcium and potassium (in the 100 to 1,000 mg/L range), and Cl, Si, Na, Mg, and K (in the 10 to 100 mg/L range). The pH of the field cell leachates was generally much lower (7-8) than in the lab protocol or lab leaching column leachates. There was little cell-to-cell variation in the concentration ranges of the various species, indicating that the upper layer of disposal medium did not have a dominating influence on the composition of the leachate.

The Extraction Procedure (EP) set forth to determine the hazardousness of waste (toxicity category) under the provisions of RCRA* was performed on the Exxon PFBC waste. The EP extractant was analyzed for the eight metallic ions specified by the regulations (Ag, As, B, Cd, Cr, Hg, Pb, and Se). None of these elements had concentration higher than the limits specified in the RCRA regulation, so the PFBC waste would likely be classed as nonhazardous in the toxicity category.

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*Resource Conservation and Recovery Act of 1976. Regulations promulgated on 19 May 1980 (40 CFR Part 261).

1.4.2 Alliance AFBC Waste Leachate Composition

Step 1 leaching of Alliance AFBC waste in the batch equilibration protocol yielded leachates with a mean calcium concentration of 1340 mg/L and a mean sulfate concentration of 1110 mg/L. The pH was also very high at 12.3 to 12.5. Other species having somewhat elevated concentrations are chloride (51 mg/L), potassium (44 mg/L) and sodium (13 mg/L). Step 1 leaching resulted in removal of 63% of the chloride, 25% of the strontium and 13% of the molybdenum from the Alliance AFBC solids. Calcium and sulfate, which had the highest leachate concentrations, were 4.5% and 8.5% removed by leaching, respectively.

With continued leaching in repetitions of Step 2 of the protocol, the leachate concentrations of the major species, calcium and sulfate, generally decreased, although sulfate decreased only slightly. For the other species examined, 14 increased in concentration and only seven decreased. The pH remained constant. Repetitions of Step 3, where the same leachate sample was repeatedly exposed to fresh waste samples, resulted in increasing concentrations for almost all parameters, except pH and magnesium, which remained constant. Aluminum, beryllium, and silicon showed a decrease followed by an increase.

Two laboratory leaching columns containing Alliance AFBC waste were constructed and operated. One of the columns had a layer of sandstone above and below the waste layer to simulate landfill cover material and substrate material, respectively, and the other column had only the upper layer of medium and the waste layer. For the latter column, calcium and sulfate were again the predominant species in the leachate samples, with ranges up to 1300 mg/L and 2000 mg/L, respectively. Chloride (range up to 1200 mg/L) and potassium (range up to 950 mg/L) also had elevated concentrations. The pH was again very high, with a value of 12. The leachates from the column with the lower sandstone layer are described below in the evaluation of attenuation of Alliance AFBC waste leachate.

Five field cells containing Alliance AFBC waste were constructed and operated. Two of the cells contained alluvium in the upper layer, and the other three cells contained shale, interburden, and limestone. The cells were operated from March, 1980 to November, 1981. During the period of operation, 24 samples were collected from the upper sample point and analyzed.

Leachates from the upper sample points for all the cells had highest concentrations (1000 to 10,000 mg/L range) for sulfate and total dissolved solids. Next highest were calcium and potassium, with concentrations generally in the 100 to 1000 mg/L range. Also significant, with concentrations in the 10 to 100 mg/L range, were silicon, sodium, and strontium. Chloride ranged from 10 to 100 mg/L in some cells and from 100 to 1000 mg/L in others. The pH values were at or near neutrality.

The RCRA Extraction Procedure was performed on the Alliance AFBC waste, and the extracts were analyzed for the eight metallic ions specified by the RCRA regulations. The results of these analyses showed that the waste is likely to be classified as nonhazardous in the RCRA toxicity category.

1.4.3 Georgetown AFBC Waste Leachate Composition

Steps 1 and 2 of the laboratory protocol were used to determine the leaching characteristics of the Georgetown AFBC waste. The species with the highest concentration in the Step 1 leachate were calcium and sulfate, with mean values of 1500 and 1400 mg/L, respectively. Other species with lower but still substantial concentrations were chloride (24 mg/L), potassium (18 mg/L), and strontium (13 mg/L). The mean pH value was 12.5. Comparison of the mass leached to the mass originally present in the solids for each species showed that chloride and strontium were leached the most, with 63% and 52% removed, respectively. Sulfate and calcium, the highest concentration species, were leached 17% and 5%. About 13% of the lithium was leached from the Georgetown AFBC waste.

Successive repetitions of Step 2 on the Georgetown AFBC waste resulted in decreasing leachate concentration trends for most species. No species showed a consistent increase in concentration with increased leaching, although barium showed an initial increase followed by a decrease. Fluoride remained constant during the Step 2 repetitions.

Extraction and analysis of the Georgetown AFBC waste by RCRA procedures showed that the waste is nonhazardous in the toxicity category.

1.5 Attenuation of FBC Waste Leachate

The attenuation of leachates from each of the three FBC wastes was evaluated separately for each of the six types of disposal media. Attenuation was studied in the lab and field for the Exxon PFBC and Alliance AFBC waste and in the lab for the Georgetown AFBC waste. Strictly speaking, the term "attenuation" refers to chemical interactions of the leachates with the disposal media wherein contaminants are removed from the leachate. Where contaminants are contributed by the media, the term "mobilization" is appropriate. However, in the interest of brevity, the term attenuation is used to refer to both types of chemical interactions between the leachate and the media in this report.

Several chemical and physical characteristics of the disposal media were determined to set the context for understanding the observed behavior of the leachate when exposed to the disposal media samples. Then the chemical changes of the leachates and the disposal media as a result of the interaction of the two was investigated for each of the three FBC wastes.

In general, attenuation was evaluated by reference to a derived parameter termed fractional attenuation. For the lab protocol results, fractional attenuation is defined as follows:

$$A_L = \frac{C_i - C_f}{C_i}$$

where: A_L = laboratory fractional attenuation

C_i = initial leachate concentration (before exposure to the disposal media)

C_f = final leachate concentration (after exposure to the disposal media)

For the field cells, fractional attenuation is defined as follows:

$$A_F = \frac{C_U - C_L}{C_U}$$

where: A_F = field fractional attenuation

C_U = concentration in leachate from upper sample point

C_L = concentration in leachate from lower sample point.

1.5.1 Composition and Leaching Properties of the Disposal Media

The composition of the disposal media was determined by binocular microscope examination and X-ray diffraction (XRD) analysis to identify the minerals present, and by sample digestion and analysis for determining chemical composition.

1.5.1.1 Disposal Media Composition

For shale, the principal identifiable minerals under the microscope were quartz, muscovite, and hematite. XRD analysis disclosed the presence of quartz, muscovite, and several clay minerals, including kaolinite, montomorillinite, and chlorite. The principal elements found by sample digestion and analysis were silicon (25%), aluminum (9%), and iron (4%). The potassium and calcium contents of the shale were 2.8% and 1.1%, respectively.

The sandstone had most of the same minerals as the shale, but with a higher proportion of quartz. Binocular microscope examination showed the sandstone to consist of 80 to 95% quartz. XRD analysis disclosed the presence of the same minerals as were found in the shale. The percentages of Si, Al, Fe, and K were virtually the same as in the shale; calcium was somewhat lower at 0.4%.

The interburden had a similar mineralogical composition to the shale and sandstone, except that it also contained about 40% coal fragments. The percentages of silicon, aluminum, and iron were 19%, 10%, and 2.3%, respectively. The percentages of silicon and iron reflected the reduced aluminosilicate component resulting from the high percentage of coal fragments. The calcium and potassium contents were 0.5% and 1.7%.

The glacial till, under microscope examination, was found to consist of about one-third limestone particles and two-thirds particles of varying composition, including mudstone, granite, schist, dolomite, sandstone, and other rock and mineral particles. A small amount of plant material was also observed. The XRD pattern for the glacial till revealed the presence of quartz, calcite, dolomite, illite, and other less important minerals. The elemental composition of the till was again typical of aluminosilicate rock, with 23% silicon, 6% aluminum, 3.4% iron, 2.4% potassium, and 5.7% calcium.

Under the microscope, the alluvium was found to consist primarily of quartz with about 5% of other minerals and rock fragments. XRD analysis revealed the presence of quartz, plagioclase, and muscovite. The alluvium contained 35% silicon, 4.1% aluminum, 3.0% iron, 1.2% potasssium and 0.1% calcium.

Microscopic examination of the limestone (study of a thin section by polarizing microscope) showed that it was composed of sparry calcite and cemented grains of fossil fragments and small pellets. The elemental composition (4% Si, 1.5% Al, 0.7% Fe, 0.8% K, and 32% Ca) reflected that it was not aluminosilicate material like the other media.

1.5.1.2 Disposal Media Physical Properties

The particle size distribution was obtained for the three unconsolidated disposal media (interburden, till, and alluvium) by sieve and pipette analysis. The alluvium contained mostly coarse silt with some very fine sand and about 10% clay material. The median grain size was about 100 microns. The interburden had a higher fine sand content than the alluvium and contained about 21% clay. The median grain size of the interburden was about 40 microns. The glacial till was more fine-grained than the other two media, with a median grain size of about 10 microns and about 39% clay-sized particles. Particle size characteristics were not obtained for the consolidated disposal media because the attenuation properties do not depend on the sizes of individual particles but on the extent of crushing before use, which is an operational variable rather than a property of the media.

All disposal media samples were examined by binocular microscope to obtain descriptions of the textural relationships and to further describe the grain sizes present. The shale was observed to range from clay shale to siltstone in grain size and was poorly sorted. It was fissile (broke up into small, plate-like pieces) and exhibited a laminar appearance. The interburden was found to be a poorly sorted, fissile shale with abundant coal fragments. The sandstone was a clayey fine sandstone with moderate sorting.

1.5.1.3 Disposal Media Leaching Properties

The leaching characteristics of the disposal media were determined to provide a basis of comparison between leachates derived from FBC wastes and leachate derived from natural geological materials and to gain insight into which species are likely to be mobilized rather than attenuated when FBC waste leachate is exposed to disposal media. The disposal media leaching characteristics were determined by laboratory protocol leaching, in laboratory control columns, and in field control cells.

Protocol Step 1 was performed on each of the disposal media with deionized water as the eluant. Overall, the highest concentrations were noted for TDS, SO_4, Ca, Mg, K, and Na. The pH values ranged from slightly acid (5.5) to slightly alkaline (8.7). For most parameters, the alluvium leachate had lower concentrations than leachates from the other media.

Six laboratory control columns, about six feet long and six inches in diameter, contained disposal media only. The columns were operated for 517 days, during which time 63 leachate samples were collected and analyzed. For all columns, the highest concentrations were noted for Ca, K, Mg, Na, Si, SO_4, and TDS. The leachates from the interburden-bearing column had higher concentrations of most parameters than the leachates from the other columns. Also, the pH was much lower (1.9 to 2.4) for the interburden column. The limestone column had elevated fluoride and sodium values relative to the other columns. The alluvium column was lower than the other columns for many parameters, notably Ca, K, Mg, SO_4, and TDS.

Two field cells, one containing shale and one containing alluvium, were constructed and operated as control cells (without any waste) to provide a basis of comparison of leachates from the cells that did contain waste. The data used for analyzing the leachate concentrations were collected after the first 60 days of cell operation.

In leachates from the shale-bearing field control cell, concentrations were highest for SO_4 (2060 mg/L), Ca (1000 mg/L), Mg (210 mg/L), K (65 mg/L), and TDS (3700 mg/L). Other parameters having substantial concentrations were TIC, TOC, Si, Na, Al, and Cl. The pH was very close to neutral. For the alluvium field cell, the highest concentrations were noted for SO_4 (130 mg/L), Ca (80 mg/L), TDS (320 mg/L), Si (14 mg/L), Mg (13 mg/L), TIC (13 mg/L), and TOC (7 mg/L). Potassium and sodium also had substantial concentrations. The pH of the alluvium cell was slightly acid (6.4). The alluvium field cell in general had lower overall concentration than the shale cell; the TDS concentration for the shale cell was more than 10 times the TDS value for the alluvium cell.

1.5.2 Attenuation of Exxon PFBC Waste Leachate

The attenuation of Exxon PFBC waste leachate was assessed for each of the disposal media by performance of Steps 4, 5, and 6 of the sequential batch equilibration protocol. Attenuation was also determined with shale in the lab leaching columns and with shale, sandstone, glacial till, alluvium, and limestone in the field cells.

Attenuation in the Laboratory Protocol

During protocol Step 4, waste leachate which was generated during Step 1 leaching of the Exxon PFBC waste was exposed to a known mass of disposal medium. The laboratory fractional attenuation (A_L) was computed using the Step 1 concentration as C_i and the Step 4 concentration as C_f in the equation noted above for A_L. Positive values of A_L for each parameter indicate that attenuation has occurred, whereas negative values denote mobilization of the parameter. Fractional attenuation for sequential exposure of fresh leachate to previously burdened media (Step 5) and of the same leachate sample to fresh samples of media (Step 6) are described below in the text. Initial (Step 4) attenuation is described in this summary.

For shale, attenuation of the PFBC leachate was indicated for all parameters for which A_L could be determined. Attenuation was greatest for Li (A_L = 1.0), Mg (1.0), Al (0.95), B (0.9), and Cr (0.95). Calcium (0.85) and sulfate (0.41) were also attenuated by the shale.

For interburden, attenuation was greatest for Li (A_L = 1.0), Ni (1.0), B (0.97), and Mg (0.97). Chloride, sodium, and fluoride were contributed to the leachate by the interburden, with A_L values of -1.1, -0.3, and -0.2, respectively. Calcium, with an A_L value of 0.25, and sulfate, with an A_L of 0.04, were both attenuated by the interburden.

Exposure to the sandstone resulted in attenuation of all parameters for which A_L was calculated. Attenuation was greatest for Li (A_L = 1.0), Mg (1.0), Na (1.0), B (0.97), and Zn (0.95). Calcium and sulfate, with A_L

values of 0.53 and 0.20, were also attenuated. Attenuation was least for silicon (A_L = 0.15) and strontium (0.18).

The strongest attenuation resulting from exposure of the PFBC leachate to glacial till was noted for Li (A_L = 1.0), Na (1.0), Mg (1.0), and B (0.94). Nickel was strongly contributed (A_L = -30), and aluminum, chromium, and silicon were also mobilized, with A_L values of -0.30, -0.21, and -2.5, respectively. Calcium (0.66) and sulfate (0.23) were both attenuated.

Exposure of the PFBC leachate to the alluvium resulted in contribution of a number of parameters, including Al (A_L = -0.6), Ba (-0.42), Cr (-0.47), Fe (-0.91), and Si (-0.66). Nickel (29) was strongly attenuated. Also substantially attenuated were Mg (1.0), Na (1.0), B (0.96), and Zn (0.91). Calcium and sulfate were both attenuated, with A_L values of 0.67 and 0.40.

For limestone, attenuation was greatest for magnesium (A_L = 0.99) and boron (0.96). Silicon was highly mobilized (A_L = -31), and several other parameters were contributed to the leachate somewhat, including Al (-1.32), Ba (-0.30), Cr (-0.43), and Sr (-0.14). Calcium (0.66) and sulfate (0.39) were both attenuated.

Attenuation in the Laboratory Leaching Columns

Attenuation in the laboratory leaching columns was evaluated by comparing the leachates from columns containing an upper layer of shale, a middle layer of Exxon PFBC waste, and a lower layer of shale with leachates from a column containing no lower shale layer. This comparison showed the lower shale layer did very little in attenuating calcium and sulate. The initial pH (=9.0) was elevated (although still lower than in the columns without the lower shale layer), but was near neutrality for most of the period of column operation. Thus pH was substantially reduced by the lower shale layer. The lower layer of shale also apparently substantially reduced the concentrations of potassium, lithium, and possibly molybdenum. Chromium, iron, and magnesium were appreciably mobilized from the shale rather than being attenuated.

Attenuation in the Field Cells

Fractional attenuation for the field cells (A_F) was evaluated using leachate concentration data from the upper and lower sample points according to the equation set forth above. Because of the wide fluctuation of concentrations observed in the early leachates from the field cells, attenuation was evaluated using mean concentrations from leachates collected after 60 days of cell operation.

Two of the Exxon PFBC field cells contained shale as duplicates; both cells showed attenuation from manganese (A_F = 0.98), lithium (0.7), and molybdenum (0.65). Strong mobilization was noted in both cells for magnesium (-0.8 to -2.7), and aluminum (-0.7). Consistent attenuation for both cells was observed for B, Cr, Cu, Fe, K, and Si. Consistent mobilization occurred for strontium, titanium, and vanadium. One cell showed mobilization and the other showed attenuation for Ba, Ca, Na, SO_4, and Zn. In one of the cells, 10 of the 20 parameters analyzed were attenuated, and 13 of the 20 were attenuated in the other cell.

The field cell containing glacial till demonstrated strongest attenuation for Mn (A_F = 0.94), K (0.83), Mo (0.82), and Sr (0.67). Strongest mobilization was exhibited for magnesium (-3.24) and aluminum (-1.55). Calcium and sulfate, the highest-concentration species in the upper sample point leachates, had A_F values of 0.02 and -0.06. Ten of the 20 parameters analyzed were attenuated.

For the field cell containing limestone, no parameters were strongly attenuated, although the A_F value was 0.32 for molybdenum, 0.21 for barium, and 0.21 for silicon. Mg (A_F = -4.4), Sr (-3.8), Al (-1.5), and Na (-1.5) were strongly mobilized from the limestone. Calcium and sulfate had A_F values of 0.07 and -0.56. Only six of the 20 parameters analyzed were attenuated.

The best attenuation in the field cell containing alluvium occurred for Li (A_F = 0.91), Si (0.59), K (0.58), and Mo (0.56). The strongest mobilization occurred for Mn (-13), Mg (-2.2), Zn (-1.3), and Al (-1.1). Calcium and sulfate had A_F values of 0.14 and -0.05. Nine of the 20 parameters studied were attenuated.

The sandstone field cell exhibited good attenuation for iron (A_F = 0.49) and silicon (0.30). Strong mobilization was observed for Mn (-9.9), Mg (-2.8), Cu (-2.1), and Al (-1.8). Only 6 of the 20 parameters observed were attenuated.

1.5.3 Attenuation of Alliance AFBC Waste Leachate

The attenuation of the Alliance AFBC waste leachate was determined in Steps 4, 5, and 6 of the laboratory protocol, in one of the laboratory leaching columns, and in five field cells. The results of the initial attenuation step (Step 4) are reported in this summary; Step 5 and 6 results are given in the text below.

Attenuation in the Laboratory Protocol

For shale, attenuation of the Alliance AFBC leachate was indicated for eight of the 19 parameters evaluated in Step 4 of the laboratory protocol. Attenuation was relatively good for Li (A_L = 0.81), Ba (0.73), Ca (0.67), and SO_4 (0.54). Strong mobilization was indicated for Si (-3.5), Cu (-1.6), V (-1.5), and B (-1.1).

In the case of interburden, attenuation was indicated for 17 of the 21 parameters examined. The best attenuation was noted for Fe (A_L = 1.0), Zn (1.0), Li (0.90), and Ba (0.84). Strong mobilization occurred for fluoride (-7) and silicon (-1.5). The two most concentrated species in the Step 1 leachate, calcium and sulfate, had A_L values of 0.55 and 0.45.

Sandstone attenuated 16 of the 21 parameters evaluated in Step 4 leaching of the Alliance AFBC waste. The highest A_L values were observed for Ba (0.96), Ni (0.89), Fe (0.88) and Al (0.82). Mobilization was not as pronounced as for some of the other media; the lowest A_L values were -0.73 for silicon and -0.44 for fluoride. The A_L values for the important species, calcium and sulfate, were 0.46 and 0.34.

For glacial till, 16 of 21 parameters examined were again attenuated. The strongest attenuation occurred for Ni (A_L = 1.0), Zn (1.0), B (0.97), and Ba (0.90). Silicon was the most strongly mobilized, with an A_L value of -6.7. Calcium (0.67) and sulfate (0.47) were again attenuated.

Attenuation by the alluvium occurred again for 16 of the 21 parameters for which A_L was calculated. The best mobilization occurred for zinc (A_L = 1.0) and boron (0.88). Most strongly mobilized were fluoride (-4.6), iron (-1.8), and silicon (-1.7). The A_L values for calcium and sulfate were 0.58 and 0.56.

In the case of limestone, 15 of the 21 parameters were attenuated. Attenuation was noted particularly for Cr (A_L = 1.0), Fe (1.0), Ni (1.0), Zn (1.0), and B (0.97). Fluoride (-1.5), sodium (-1.4), and silicon (-1.3) showed the strongest mobilization. The calcium and sulfate A_L values were 0.50 and 0.44.

Attenuation in the Leaching Columns

Two laboratory leaching columns containing Alliance AFBC waste were constructed and operated. One of the columns had three layers (upper layer of sandstone, middle layer of Alliance waste, and lower layer of sandstone) and the other had two layers (the lower layer of sandstone was omitted). Comparison of the leachates from the column containing the lower sandstone layer with the other column disclosed the attenuating influence of the lower layer.

This comparison showed that for both columns the predominant species were calcium and sulfate. Some indication of attenuation of calcium (but not sulfate) was observed. Chloride and potassium were also high in the leachate from both columns. The leachate pH, which was at 12 in the column without the lower layer, was near neutrality (7.0 to 7.8) in the other column. Magnesium appeared to be mobilized from the lower sandstone layer. Lithium was apparently somehwat attenuated by the sandstone.

Attenuation in the Field Cells

Five field cells were constructed with Alliance AFBC wastes. The disposal media used were interburden, alluvium (in duplicate cells), limestone, and shale. Attenuation was evaluated in the same way as in the Exxon PFBC field cells, by using the mean concentrations of leachate samples from the upper and lower sample points after 60 days of operation. The field fractional attenuation, A_F, was computed by the same formula.

The field cell containing interburden showed attenuation for 6 of the 19 parameters evaluated. Very strong mobilization was indicated for Fe ($A_F = -5070$), Al (-2970), Ni (-1490), and Zn (-953). Also substantially mobilized were B, Cr, Mn, and V. Only molybdenum and sodium were appreciably attenuated, with A_F values of 0.75 and 0.59. Calcium and sulfate, the most concentrated species in the upper sample point leachates, had A_F values of -1.01 and -5.82. The interburden field cell was clearly experiencing chemical changes similar to those often observed in acid mine and waste pile drainage.

The duplicate alluvium field cells had generally consistent results; one of the cells showed attenuation of 8 of the 19 parameters evaluated, and the other showed attenuation of 12 of the 19 parameters. The best attenuation shown by both cells was for K ($A_F = 0.98$), Sr (0.9), V (0.9), Si (0.82), Cr (0.7), and SO_4 (0.7). Strong mobilization was observed for Mg (-121), Mn (-57), Al (-7.4), and B (-8.3). Calcium showed moderate attenuation in one cell and moderate mobilization in the other.

The limestone-bearing field cell showed mobilization of 17 of the 21 parameters evaluated. Most strongly mobilized were Mg (A_F = -399), Ti (-21), Al (-17), Zn (-3.6), and Ni (-2.6). Only strontium, manganese, and potassium were appreciably attenuated. Calcium and sulfate had A_F values of -0.2 and -0.6.

The Alliance AFBC field cell containing shale showed mobilization of 15 of the 21 parameters examined. Greatest mobilization was seen for Mg (A_F = -257), Al (-35), Zn (-3.7), and Fe (-2.6). Moderately good attenuation was seen for lituium, potassium, and strontium. Calcium and sulfate had A_F values of -0.63 and -0.85.

1.5.4 Attenuation of Georgetown AFBC Waste Leachate

The attenuation of Georgetown AFBC waste leachate was evaluated in Step 4 of the laboratory protocol. When the leachate was exposed to shale in Step 4, attenuation occurred for 11 of the 16 parameters investigated. Attenuation was strongest for lithium and magnesium, with A_L values of 0.99 and 0.82. Strong mobilization occurred for silicon (-3.3) and total organic carbon (-1.2). Calcium and sulfate, the most concentrated species in the Step 1 leachate, were both attenuated, with A_L values of 0.6 and 0.32.

For the interburden, Step 4 attenuation was indicated for 12 of the 16 parameters. Attenuation was strongest for nickel, with an A_L value of 1.0. Mobilization was greatest for fluoride (-1.0) and sodium (-0.6). Calcium (0.65) and sulfate (0.17) were both attenuated by the interburden.

Attenuation occurred for 12 of the 16 parameters for the sandstone, with the best attenuation noted for nickel (A_L = 1.0) and lithium (0.91). Fluoride and sodium, with A_L values of -0.59 and -0.32, were moderately mobilized. Calcium (0.54) and sulfate (0.16) were both moderately attenuated.

Eleven of the 16 parameters were attenuated when the Georgetown AFBC leachate was exposed to glacial till in Step 4. Best attenuation was observed for lithium (A_L = 0.87) and chloride (0.74). Strongest mobilization occurred for fluoride (-1.9) and silicon (-1.8). Calcium and sulfate had A_L values of 0.61 and 0.24.

For alluvium, 12 of the 16 parameters showed attenuation, with best attenuation for lithium (A_L = 1.0) and nickel (1.0). No strong mobilization of any of the metallic cations was observed. Calcium and sulfate, with A_L values of 0.54 and 0.36, were again moderately attenuated.

In the case of limestone, 12 of the 16 parameters studied were again attenuated. No strong attenuation occurred for any of the metallic parameters, but fluoride (A_L = -3.1) and sodium (-2.4) were strongly mobilized. Calcium (0.47) and sulfate (0.29) were again attenuated.

1.6 Statistical Prediction of Field Behavior of FBC Waste Leachates Based on Laboratory Shake Test Results

As noted, one of the goals of this investigation was to determine the feasibility of developing a method of reliably predicting the leachate generation (and attenuation) behavior of FBC wastes under landfill disposal conditions. The hope was that the field behavior might be predicted on the basis of simple and inexpensive laboratory tests of the waste. Two empirical but rigorous statistical approaches were taken to predict the chemical behavior of FBC wastes after disposal in landfills. Both approaches involved the development of statistical models from laboratory leaching data to predict field leachate properties. An extensive statistical analysis of leaching and attenuation data for Exxon PFBC and Alliance AFBC waste was performed in the first approach. A feasibility study for the second approach employed leaching data for the PFBC waste.

The two methods differed in the steps used to develop the statistical models. In the first approach, termed the "direct" method here, a model was developed directly to predict the concentrations of a particular species as a function of volume of leaching solution per mass of waste leached. The concentrations of other species did not come into play. In the second approach, termed the "indirect" method, a regression model was first developed in which the concentration of a chemical species was predicted in terms of the concentrations of other chemical species at the preceding batch equilibration protocol leaching step and possibly pH at the preceding or current leaching step. Subsequently, transformations were made through a set of mathematical steps to produce models which predicted concentration as a function of volume per mass.

The direct and indirect methods were similar in the following respects:

1. Laboratory data were used to develop models for predicting concentrations (or a function thereof) of the different chemical species. In this step, field data were not used.

2. The model development was accomplished by using regression analysis.

3. A separate model was ultimately produced for each chemical species. In the leaching models, concentration was expressed as a function of volume per mass. In the attenuation models (discussed in the direct but not the indirect method), fractional attenuation was also expressed as a function of volume per mass.

4. Thus, the end result of both approaches was the same: a model to predict concentration (or a function thereof) as a function of volume per mass. Since volume per mass is a normalized quantity, the models can be used to predict field conditions.

For the sole purpose of developing a model which predicts concentration in terms of volume per mass, the direct method is simpler and less demanding both in terms of labor and computer time. In addition, the direct method ensures that non-negative, real-value leaching concentrations are predicted. On the other hand, the indirect method produces intermediate results which can be interpreted from the standpoint of causal relationships in the leaching process. However, it must be pointed out that statistical correlations do not automatically imply that a cause-and-effect relationship exists. A disadvantage of the indirect method is that it is possible for mathematical instabilities to develop.

Results of the Direct Method

In the direct method of analysis, an analysis of leaching behavior was first performed. Models were developed from laboratory data to predict leachate concentrations. When these models were developed, those chemical species whose concentrations were predominantly near or below detection limits were excluded. Subsequently, an analysis was performed to quantify the agreement between observed field concentration and corresponding values predicted from the laboratory models. It was found that for the 13 species investigated in leachates from the Exxon PFBC waste, the mean agreement between the observed field values and the laboratory-predicted field values was within a factor of 10 in 11 cases, a factor of 5 in 8 cases, and a factor of 2 in 3 cases. For 19 species investigated in leachates from the Alliance AFBC waste, the mean agreement was within a factor of 10 in 17 cases, a factor of 5 in 16 cases, and a factor of 2 in 10 cases. Thus, laboratory models are capable of predicting field trends within an order of magnitude in most cases. The difference between the laboratory-predicted and field-observed values was statistically significant for most species, however.

The prediction of field data involved an extrapolation, since the laboratory volumes of leachate per unit mass of waste leached were much larger than those for the field cells. Further investigation showed, however, that the differences between field-observed and laboratory-predicted values are not attributable wholly or predominantly to the extrapolation. Actual differences between the behavior of the laboratory and field chemical systems are believed to explain a significant part of the discrepancies between observed and predicted values.

It was found that prediction of field fractional attenuation (A_F) values by models developed from laboratory (A_L) values was not possible in most cases. The reasons were scatter in the fractional attenuation data and dissimilarity in the trends observed in the field and the lab. It should be mentioned that fractional attenuation is a derived quantity, involving concentrations before (C_b) and after (C_a) contact with the disposal medium:

$$A = \frac{C_b - C_a}{C_b}$$

If C_b and C_a are small (say, near the detection limit), the ratio can have a large uncertainty. Due to division by the small value C_b, the ratio can be large in magnitude even when the concentrations are small. This problem was addressed in part by not developing models for species with predominantly undetected C_b values; this exclusion was no sacrifice, since the fractional attenuation is not of practical importance if the concentration before contact with the medium is very low or undetected.

Results of the Indirect Method

For the indirect method, more limited investigation was undertaken to assess the overall feasibility of the approach. Only leaching (no attenuation) data were used. The Exxon PFBC waste data but not the data from the two AFBC wastes were used. The analysis was performed using lab protocol Steps 1 and 2 data and upper sample point leachate data from the PFBC field cell containing shale in the upper layer.

The principal finding of the modelling by the indirect method was that the species fell into two groups. In the first group, consisting of SO_4, Si, Cr, Ba, Na, Fe, Ca, Zn, and Sr, the species were self-controlled; that is, the concentration (at a given extraction step) of one of these species was related to concentrations (in the preceding step) of species within the group. Sulfate and silicon were individually self-controlled. Concentrations for the second group, consisting of Mg, B, F, Cl, and Al were largely controlled by the first group. It was observed that pH did not play a crucial role as a predictor variable. This is not surprising, since pH varied only between 11.0 and 12.0 during the sequence of laboratory extractions for the Exxon PFBC waste.

For predicting field observed values from the laboratory, the indirect method was close for barium and strontium and nearly as close for zinc. Sulfate was predicted within a factor of two, and calcium and chromium were predicted within a factor of three. In most cases, the predicted values were higher than the observed values with the exception of sulfate, silicon, and sodium.

1.7 Overall Assessment of the Acceptability of FBC Wastes for Land Disposal

An overall assessment of the environmental "acceptability" of the FBC wastes for land disposal was performed by comparing: (1) the bulk composition of FBC wastes with that of the disposal media; (2) the quality of FBC waste leachate with similar leachate derived from the disposal media; and (3) the concentrations of various parameters found in FBC waste leachate with accepted water quality standards and criteria.

1.7.1 Comparison of FBC Waste and Disposal Media Composition

When the bulk solids compositions of the three FBC wastes were tabulated with the compositions of the six disposal media, it was found that for most parameters the composition of the wastes and disposal media were quite comparable. The wastes had a higher calcium content (22-32%) than the media, which had 0.1-1% calcium. The exception was limestone, which had 32% calcium. The sulfate content of the Exxon PFBC and Alliance AFBC waste was also much higher (13-23% sulfate) than the disposal media, which had sulfate contents ranging from less than 0.1% to 0.6%. The Georgetown AFBC waste had an anomalously low sulfate content of 0.5%.

The magnesium content of the Exxon PFBC waste was much higher (12%) than the magnesium content of either of the AFBC wastes (0.5% magnesium) or of any of the disposal media, which had magnesium contents ranging from 0.3 to 1.7%. The potassium contents of the Alliance and Georgetown AFBC wastes were lower (0.4 - 0.5%) than in the Exxon PFBC waste (2.2%) or in the disposal media (ranges from 0.8 to 3.0%).

Except for limestone, the disposal media had higher aluminum contents (4.1 - 9.5%) than the FBC wastes (2.0 - 2.9%). The aluminum content of the limestone was 1.5%. A similar situation was found for silicon, where the media contents were 19-35% (except for limestone, which had 4.1% silicon). The silicon content of the FBC wastes ranged from 4.2 to 5.8%. The iron contents of the wastes and five of the disposal media were very comparable, with an overall range of 2.3 - 5.3%. Limestone was again the exception, with an iron content of only 0.7%.

Most of the rest of the parameters were similar in concentration for the wastes and disposal media. The parameters whose concentrations were thus similar were B (except Alliance AFBC waste, which was much lower), Ba, Be, Cd, Co, Cr, Cu, Mn, Na (except Alliance waste), Ni, Sr (except Alliance), V (except Alliance), and Zn (except Exxon waste). The wastes had generally higher chloride contents than the disposal media. Lithium in the Georgetown waste was comparable to five of the disposal media. Lithium was lower in the Exxon and Alliance waste and was more comparable to the limestone medium lithium values. Molybdenum was higher in the wastes than in all the media except the till. Titanium was higher in all the media (except limestone) than in the waste.

In summary, the FBC wastes contained about the same amount of the minor and trace elements as the disposal media. The wastes contained more Ca, Mg (Exxon PFBC waste only), SO_4 (except Georgetown AFBC waste), Cl, and Mo. The media were generally higher than the wastes in Al, K, and Si content.

1.7.2 Comparison of FBC Waste and Disposal Media Leachates

A comparison was made of the concentrations of several species in the FBC waste leachate with similar concentrations in leachates derived directly from samples of the disposal media. For the laboratory protocol studies, Step 1 and 2 leachates derived from the wastes and disposal media were compared. Most of the waste leachates were similar to or somewhat higher than the disposal media leachate concentrations. B, Ca, Li, Mo, Sr, SO_4, and TDS were generally significantly higher in the waste leachate than in the disposal media leachate. The pH of the waste leachates was also much higher than in the media leachates. Only the fluoride concentration was significantly higher in the media leachate than in the waste leachate (for the Alliance AFBC waste only).

In the field cell studies, the leachate data from the upper sample point of the field cells containing waste was compared to the leachate data from the control cells which contained disposal media only. Nearly all of the comparisons showed that the waste leachate and disposal media leachate were similar or only slightly below or above each other in concentration. Only for chloride, lithium, and strontium were the waste leachates more than an order of magnitude above the disposal media leachates in concentration. No parameter was generally as much as an order of mganitude lower for the waste than the disposal media in the field studies.

Overall, the comparisons of the FBC waste leachates with leachates from the disposal media shows that the waste leachates can generally be expected to be higher in B, Ca, Li, Mo, Na, SO_4, Sr, and TDS. The pH, although very high in the waste leachates in the lab studies, was generally not elevated in the field studies. Chloride was higher for the Alliance AFBC wastes than for the disposal media. The parameters which were higher for the disposal media than for the waste were few and included only fluoride in the lab studies. No parameters were as much as an order of magnitude higher for the waste than the media in the field program.

1.7.3 Comparison of FBC waste Leachate Quality With Water Quality Standards and Criteria

As a further means of evaluating the environmental acceptability of FBC wastes, the leachate concentrations that were observed were systematically compared to accepted water standards and criteria. The comparison was made both on non-attenuated and attenuated leachates.

Opinion concerning "safe" ambient concentrations and concentrations in leachates and other discharges to the environment is quite varied. A survey of several authoritative sources was performed to form the basis of comparison for the FBC waste leachates. These sources include the Primary and Secondary Drinking Water Regulations (Reference 1 and 2), Resource Conservation and Recovery Act Regulations (Reference 3), the Quality Criteria for Water (Reference 4), and the Multimedia Environmental Goals (Reference 5).

From these sources, the most stringent standard or criterion was selected for purposes of the comparisons. In some instances, the most stringent value may not be directly applicable to likely avenues of FBC waste leachate discharge to the environment. The purpose of drawing a comparison in those instances was to emphasize where the FBC leachate concentrations do not exceed even the most stringent value. For many of the parameters, the most stringent criterion possibly is too low and could be increased to allow for dilution and dispersion of FBC leachate in the environment.

A comparison of the leaching and attenuation results showed that several parameters exceeded the standards in almost all phases of the study (both lab and field), including B, Ca, Cr, SO_4, and TDS. The standard for pH was exceeded in all phases of the lab investigation, and K, Mn, and Ni generally exceeded the standard for all phases of the field study. Ba, F, Fe, Mo, Sr, and Ti were generally below the standards for all phases of the investigation. Magnesium was below the standard for the lab studies. In the field studies, only pH was consistently within the standard (besides the parameters mentioned above for both the lab and field studies).

There was little or no difference between the laboratory and field results in terms of parameters which were consistently above or below the standard. There appeared to be no significant difference in the field cells between cells containing disposal media only and cells containing both waste and disposal media.

1.8 Compatibility of Landfill Liner Materials with FBC Waste Leachate

In the event that some future FBC waste streams are classed as hazardous and will have to be disposed of in secure landfills requiring liners, an investigation of the compatibility of commonly used landfill liner materials with FBC waste leachate was performed. Under certain conditions, such as in shallow water table conditions or where groundwater is used as a nearby drinking water source, even nonhazardous FBC waste landfills may be required to use liners.

The objective of the liner investigation was to determine if the liner integrity is reduced as a result of exposure to FBC waste leachate by using several chemical and physical tests. Six synthetic liner materials and one clay were tested:

- Neoprene;
- Polyvinyl chloride (PVC);
- Chlorinated polyethylene (CPE);
- Chlorosulfonated polyethylene (Hypalon);
- Butyl rubber;
- Ethylene propylene diene monomer (EPDM) rubber; and
- Sodium bentonite clay.

Leachate from protocol Step 1 leaching of the Exxon PFBC waste was used in the experiment. For the synthetic liners, uniformly sized strips of the liner material were attached to a rack and immersed in a tank containing the leachate. The bentonite clay was mixed with the leachate, and the mixture was continuously agitated. Degradation of the synthetic liner materials was monitored by removing samples of the liner strips monthly and testing them for tensile strength. The leachate was also sampled monthly and analyzed for total organic carbon (TOC) concentration to indicate the release of liner carbon constituents to the leachate. In addition, the liner surfaces were examined by scanning electron microscope for direct visual evidence of liner degradation.

For the clay liner material, degradation was monitored by monthly sampling and analysis of the clay by X-ray diffraction to detect clay mineral breakdown. Also, the leachate was analyzed for aluminum as a means of detecting the release of clay mineral components to the leachate solution. The investigation of both the synthetic liner and the clay liner continued for 18 months.

For the synthetic liners, Hypalon was the strongest overall. Four of the six liners (EPDM rubber, butyl rubber, neoprene and CPE) had very similar strengths which were lower than the Hypalon strength. PVC had a strength about midway between Hypalon and the other four liners. All of the liners showed a decrease in strength with increasing time of exposure to the leachate. In terms of percentage of the maximum tensile strength observed, the greatest drop in strength was observed for CPE, with a decrease to 50% of maximum. The least decrease in strength was seen for the Hypalon and EPDM rubber liners (to 70% of maximum).

Under SEM magnification, only two of the six liners showed evidence of significant deterioration resulting from exposure to the Exxon PFBC waste leachate. Most of the liners could not be easily observed because of the formation of a precipitate on their surfaces. The TOC concentration trends showed the greatest gain in carbon content in the leachates containing the Hypalon and CPE liner. EPDM rubber and Neoprene showed the lowest increases in TOC content in these leachates.

In general, the liner showing the least compatibility with the Exxon PFBC waste was CPE, which showed the clearest sign of chemical degradation under SEM observation and by the TOC analysis. Its tensile strength was in the group of four liners having the lowest strength. Hypalon, on the other hand, showed signs of chemical degradation in the SEM and TOC studies, but its strength (which was initially high) remained the highest of all the liners for the duration of the experiment.

X-ray diffraction analysis of the bentonite clay that was immersed in the PFBC waste leachate revealed that one of the first changes to occur was a change in the clay from a sodium- to a calcium-montmorillonite as the calcium in the leachate replaced the sodium ions in the interlayer positions of the montomorillonite. Although one of the peaks on the XRD patterns changed slightly as the experiment progressed, which may have been an indication of incipient breakdown of the aluminosilicate structure of the clay, the patterns in general showed no major structural change in the clay. After the first month, a new mineral, ettringite, was identified in the XRD pattern, which indicated a possible change in the basic structure of some of the initial clay material.

Throughout the experiment, the concentration of aluminum in the leachate was at or below the levels found in the leachate prior to interaction with the clay. Thus, the aluminum concentration data did not indicate breakdown of the aluminosilicate structure of the clay over the 18 months of the test.

In general, the liner materials tested were found to be quite compatible with Exxon PFBC waste leachate insofar as could be determined in this relatively short and simple investigation. If there had been strong incompatibility of the liners with the leachate, then the degradation would have been readily detected in this program. Although no strong incompatibility was observed, some of the polymer liners did show a significant loss of tensile strength during the 18 months of leachate exposure. The formation of a new mineral phase, ettringite, as the probable reaction product of the montmorillonite and the high-calcium leachate could also lead to eventual breakdown of the effectiveness of the clay or a liner material. Additional study with a specific waste would be advisable before any of the liners are used at a future FBC waste disposal site.

1.9 Conclusions

For the three representative FBC wastes analyzed, the waste composition was remarkably similar to typical landfill substrate materials, except for the calcium and sulfate content. For these two parameters, the waste content was from 20 to 200 times the content of the aluminosilicate disposal media (shale, interburden, sandstone, and alluvium). Magnesium in the Exxon PFBC waste was from six to 30 times the magnesium content of the disposal media. Chloride was from three to eight times higher in the waste than in the disposal media. The aluminosilicate media were from two to five times higher in aluminum and from four to seven times higher in silicon than the wastes. The other chemical species analyzed were quite similar in the waste and disposal media content.

The leachates generated from the three FBC wastes in the batch equilibration protocol were generally high in pH (>11) and near saturation in calcium and sulfate upon repeated extraction, to ratios of 80 or greater. Total dissolved solids and conductivity were high and essentially tracked the pH, calcium and sulfate. Comparison between laboratory batch results, limited laboratory column results, and field column results did not demonstrate consistency. In some instances, batch extraction concentrations exceeded laboratory column and field column values of comparable or lower VPM ratio. For other species the reverse was observed and for some species, concentrations were roughly equivalent across experimental systems and waste types.

The most notable aspect (and potentially a major factor where differences were observed) was the consistenly low field cell effluent pH values, both above and below the attenuation layer. Laboratory leaching columns did not replicate this behavior for either the Exxon PFBC or Alliance AFBC waste even though the laboratory columns were operated in a manner designed to simulate the field cells. The internal carbon dioxide environment and subsequent armoring of particles in the field cells must have been different than for the laboratory columns. Clearly, the sealed containers and system agitation set the batch procedures apart in this regard.

When leaching behavior was examined as a function of extent of leaching by plotting concentration versus VPM, consistent release behavior was not always seen for all elements across the three experimental configurations for the two wastes studied in each of the three configurations or even for certain species for a single waste for all three systems. Similarly, a consistent relationship was not seen for solid phase concentration and leachate concentration for all elements across the three wastes.

Most species other than calcium, sulfate and hydroxide were low in concentration (after initially high values when column leaching is performed). Some evidence of elevated boron concentrations was seen for the Exxon waste and to a lesser extent for the Alliance waste. Typically, however, most concentrations were quite low, especially for toxic or heavy metals.

The leachates from the wastes and disposal media had compositions which generally reflected the solids compositions, at least for the laboratory protocol results. Calcium, sulfate, and TDS were all substantially higher in the protocol leachates from the wastes than in similar leachates from the disposal media. The pH was also much higher in the waste leachates than the disposal media leachates in the laboratory protocol. There was not much difference in the magnesium content of Exxon PFBC waste leachates and the magnesium content of disposal media leachates in the lab protocol results. Other parameters had about the same concentrations in the waste leachates and disposal media leachates.

The field cell leachates were overall less reflective of the solids composition of the wastes from which they are derived than the protocol leachates. Leachates from some of the waste-bearing field cells were definitely higher in calcium and sulfate than similar leachates from the field control cells, but other waste-bearing cells were not higher. Magnesium was generally lower in leachates from both the Exxon PFBC and the Alliance AFBC field cells than in leachates from the control field cells. The pHs of leachates from the waste-bearing field cells were near neutrality and were thus comparable to the media-bearing cells. The field cell leachates were all much lower in pH than the waste leachates from the laboratory protocol.

All three FBC wastes tested were found to be nonhazardous in the toxicity category as determined by procedures defined in regulations developed pursuant to the Resource Conservation and Recovery Act of 1976.

The attenuation of FBC waste leachate was found to be quite variable for different wastes, for different disposal media, and for laboratory and field conditions. Overall, strong attenuation was observed for more species in the laboratory protocol than in the field cells. More parameters were found to exhibit strong mobilization in the field cells than in the protocol. About the same number of parameters experienced strong attenuation and strong mobilization in the laboratory protocol.

The attempt to show statistically reliable correlation between laboratory leaching results and field cell leaching behavior was successful for some species in the leachate generation phase when the direct (best-fit polynomial) method was used. There was little success for any species in the leachate attenuation phase, however. The indirect method, which used the lab leachate concentrations of several species in predicting the field concentration of each species, was attempted only for the leachate generation phase as a feasibility study for the approach. Relatively good prediction of field concentrations for three species (calcium, strontium, and zinc) was achieved.

The liner compatibility investigation showed that there is little chance of immediate or drastic breakdown of commonly-used landfill liners when they are exposed to FBC waste leachates. However, there was some indication of loss of integrity (tensile strength and organic carbon content) of the organic-based liners during the 18 months of the study. The sodium bentonite clay also did not show rapid basic structural breakdown when it was exposed to the FBC waste leachate. However, there was rapid exchange of calcium for the sodium in the clay interlayer position. This exchange, and the formation of a new mineral phase (ettringite), which may have been the reaction product of the clay with the leachate, may indicate a possible long-term loss of the integrity of a clay liner. Thus, when these materials are being considered at future FBC waste landfills (either organic based or clay liners), tests should be performed with samples of the waste to be disposed to be sure that liner breakdown will not occur.

Overall, the findings of this investigation show that with proper consideration of waste-specific and site-specific factors and with good engineering practice, the disposal of wastes should not be an inhibitive factor in the development and use of the FBC energy conversion technology. The wastes do not contain (or release to leachate) large concentrations of highly toxic species or other species that are extremely hazardous to human health or the environment. There is some potential concern for certain species, such as calcium and sulfate, which will need to be addressed at future disposal sites, but proper design and operation should allay these concerns. It appears feasible to use readily available liner materials necessary in the design of FBC landfills.

2.0 INTRODUCTION

Fluidized bed combustion (FBC) is an emerging energy technology that holds promise both for higher efficiency of energy conversion and minimization of adverse impacts on air quality. FBC is similar to conventional combustion in that a fuel (usually coal or combustible solid waste) is burned to generate steam for power production, space heating, or an industrial process. However, FBC differs from conventional combustion in the operation of the boiler. In a fluidized bed combustor, the fuel is held in entrainment suspension by air that is forced at high velocity through an air distribution grid at the bottom of the combustor. In a coal-fired fluidization bed combustor, the coal is mixed with a sorbent material (limestone or dolomite) before input to the combustion.

A major advantage of FBC lies in the fact that high-sulfur coal can be burned without the use of flue-gas desulfurization equipment to meet air quality standards. During combustion, the sulfur in the coal is oxidized to sulfur oxides as in conventional boilers. However, the sulfur oxides react with the sorbent material in the fluidized bed instead of being carried out to the atmosphere in the flue gas. Additonally, because of the lower combustion temperatures (about 1500°F) in FBC, the formation and emission of thermal NO_x is avoided.

Although FBC has the environmental advantage of reduced SO_2 and NO_x in the flue gas, the solid residues generated are larger in quantity and have different properties from conventional combustion waste products because of the large amount of sorbent material used. Because of the large quantity and potential environmental implications of solid wastes from FBC, the Industrial Environmental Research Laboratory (IERL) of the Environmental Protection Agency has initiated a comprehensive effort for characterizing

FBC residues and emissions and their potential environmental effects. This investigation, which is being performed under Contract 68-02-3103, is a major part of the IERL environmental characterization efforts for FBC.

2.1 Scenario FBC Waste Disposal Operations

FBC solid residue has potential for use as concrete additives, as aggregate in asphalt and concrete, as roadbed aggregate, and as a soil conditioner. Some residues may be disposed of in the ocean, although this method of waste disposal is gradually being discontinued. However, it is likely that the bulk of FBC waste that will be generated when the technology becomes more widespread will be disposed of in landfills. Thus, this investigation has been structured with the assumption that most future wastes will be landfilled. During the performance of this study there were very few commercial FBC plants in operation, so there are no representative FBC landfill operations to serve as a guide. Therefore, in order to provide balance for the study, a set of "typical" future FBC waste disposal operating conditions has been assumed. The scenario is based on landfill operation for other types of relatively homogeneous, large-volume solid wastes, such as conventional utility wastes.

In the scenario condition, the solid residuals generated in FBC combustors will be brought to ambient temperature before temporary storage at the plant site. From temporary storage the wastes will be pneumatically loaded at appropriate intervals into closed bulk carrier type trucks and will be hauled to the treatment/disposal site. It is assumed that the disposal site will be sufficiently close to the plant to allow transportation by truck. At the disposal site, the wastes will be removed from the trucks and again placed in temporary storage containers, such as silos. From the silos the wastes will be transferred to a facility where water will be added in the proper stoichiometric amounts so that hydration reactions and resultant heat release can occur under controlled conditions. Hydration under uncontrolled conditions can result in rapid (sometimes explosive) steam generation. If stabilizing additives are required for the wastes, which is unlikely, they will also be added during this step.

The primary purpose of the treatment step is to prepare the wastes so they can be safety disposed in a hydrated and thermally stable form. It is assumed that after hydration the wastes will still be in a solid form suitable for landfill disposal; pond disposal is generally recognized to be unnecessary and undesirable.

It is further assumed that most disposal sites will be devoted solely to FBC wastes. Codisposal with other types of wastes is not explicitly considered in this program, although codisposal with certain other wastes may present distinct advantages in the same way that mixing and codisposal of ash from conventional coal-fired boilers with sludge from flue gas desulfurization equipment may increases the stability of both wastes. Codisposal is a potentially fruitful area of future FBC waste investigations.

After treatment, the FBC wastes will be transported to the landfill for final emplacement. If the waste disposal site is operated as a traditional landfill, then its geometry can be postulated. For a trench type landfill, there will be tabular bodies, about ten feet thick and twenty feet wide, and perhaps a few hundred feet long, spaced on approximately fifty-foot centers. For an area landfill, there will be a large number of small cells, with approximate dimensions of 10 x 20 x 20 feet. The cells will be separated by two- to three-foot earthen walls. The aggregate of cells will comprise a large tabular body ten feet thick and few hundred feet wide and long. Two or more such bodies might be superposed. While actual landfill sites accommodate the existing topography, this general concept of geometry is useful for purposes of this investigation.

2.2 Focus on the Hydrologic Component of the Environment

The primary concern in assessing the environmental acceptability of landfilling FBC waste is on the potential hydrologic impacts, including both surface-water and groundwater impacts. There are two reasons for this emphasis. First, the hydrologic systems are the environmental components that are most likely to be adversely affected. Second, the other major environmental components, when affected by solid waste disposal operations, are often affected by means of contaminated groundwater or surface water. Thus, the other components are affected adversely only when the hydrologic components are affected.

For example, the potential adverse effects of FBC wastes on both terrestrial and aquatic systems occur via hydrologic systems. Aquatic habitats and streams would most likely be affected as a result of inflow of contaminated surface water or groundwater. Terrestrial plants downgradient from the disposal site could be affected by contaminated groundwater if the plants are taking water from below the water table. Wildlife could be impacted by taking water from streams that are contaminated by surface runoff or inflowing groundwater from the disposal site.

Because of the potential direct impact of FBC solid waste disposal on surface water and groundwater, and because the impacts on most other environmental components occur via hydrologic systems, the emphasis of this study is placed on the hydrologic impacts. It is assumed as a part of the scenario disposal conditions that the landfill will be emplaced above any local groundwater table in accordance with good engineering practice. Generally, at least five feet of unsaturated substrate will underlie the waste. The substrate can aid in attenuation of contaminants and improve the quality of leachate from the wastes before the leachate reaches groundwater. The release of contaminants from landfilled wastes is generally greater if the wastes are below the water table and remain saturated than if they are in the unsaturated zone where they are leached only periodically by infiltrating precipitation. A more detailed analysis of the interaction of a typical landfill with the hydrologic environment is given in Appendix A.

2.3 Environmental Regulatory Context

The principal federal legislation that will control future FBC waste disposal practices is likely to be the Resource Conservation and Recovery Act of 1976 (RCRA). This law, and the regulations that have been developed in response to it, provide a means of making a distinction between hazardous and nonhazardous wastes. Hazardous wastes are controlled from the point of origin to the point of final disposal by means of a manifest system and by requiring hydrologically isolated ("secure") disposal sites.

Less stringent control is imposed on nonhazardous wastes in that no manifest system is required, and leakage from the disposal site is permitted as long as no underground drinking water source beyond the solid waste boundary is contaminated. Most future FBC wastes will be classed as nonhazardous under RCRA (see Section 3.0) and will not require a secure landfill for disposal. Some FBC wastes from utility applications are at least temporarily exempted from the provisions of RCRA altogether.

One of the principal purposes of this investigation was to provide an information base for future regulatory and permit programs for FBC wastes. This data base is intended for use as a point of reference for preparing the stipulations of permits for future FBC waste disposal sites.

2.4 Objectives and Scope

With the emphasis of this investigation on the hydrologic impacts of the disposal of FBC wastes in a nonsecure landfill, the objectives are related to the generation of leachate from the waste in a landfill, the potential attenuation of the leachate by the geologic substrate, and the formation of groundwater contamination plumes. Thus, a major focus of the program is on determining the composition and physical properties of FBC wastes, assessing the characteristics of leachate generated from the wastes, and evaluating how the leachate is attenuated when exposed to typical geological substrate materials.

During the developmental stages of the program, the decision was made to try the sequential batch extraction approach for determining the leaching properties of FBC wastes and for assessing the attenuation properties of the leachates. The principal reasons for selecting the batch extraction approach was that such tests are easy to perform, they can be performed rapidly and at low cost, and they are widely accepted as a method for determining the leaching properties of wastes. It was also recognized that despite these advantages, the operative chemical processes in a batch extraction may be quite different from the processes that actually occur in landfill conditions, principally because of the vast difference in the ratio of eluant volume to mass of waste being leached. Thus, the program was structured to include large field cells to more closely simulate the chemical conditions in an actual landfill. Leachates were obtained from the field cells at a point after generation from a waste layer and at a second point after attenuation by a layer of geological substrate material.

A major goal of this program was an attempt to develop a method of predicting the chemical composition and behavior of FBC waste leachate in landfill conditions on the basis of the simple and inexpensive batch extraction tests of the waste. Considerable effort was made to rigorously relate the laboratory and field results using conventional statistical techniques.

In the event that some FBC wastes are classed as hazardous in the future, a component of this study was devoted to the investigation of the compatibility of FBC waste leachates with commercially available liner materials that could be used to provide hydrologic isolation for secure landfills. Liners may also be used in nonsecure landfills under certain conditions as well, such as where there is a shallow water table or where water is withdrawn nearby for drinking water.

In order to accomplish the overall aims of the investigation, several specific objectives were formulated for the program as follows:

- Determination of the chemical composition and physical properties of representative FBC wastes and typical landfill substrate materials (termed "disposal media" here);

- Determination of the composition of leachate from the laboratory sequential batch equilibration ("shake") tests of the FBC wastes;

- Assessment of the attenuation of FBC waste leachate when exposed to typical disposal media using the shake tests;

- Sampling and analysis of leachate from large field cells simulating actual landfill conditions;

- Statistical correlation of the results of analyses of leachates from the laboratory shake tests and leachates from the field cells; and

- Assessment of the compatibility of landfill liner materials with FBC waste leachate.

The detailed procedures used to accomplish these objectives are outlined in Section 3.0.

2.5 Report Organization

This report proceeds systematically through the results of a relatively complex investigation. Section 3.0 provides a summary of the approach and methods used in the study. Following sections present the data and interpretation for the chemical analysis of FBC wastes and the leachates derived from them. Section 4.0 begins by delineating the solids composition and physical properties of the FBC wastes. The leaching characteristics of the wastes are then described in Section 5.0. Each type of waste is discussed in turn, and a comparison among the wastes is made.

Section 6.0 describes the composition and physical properties of the disposal media to provide the context for assessing the attenuation of FBC waste leachate when exposed to typical landfill substrate materials. The leaching properties of the disposal media are also described to provide the basis for estimating the contribution of species (where mobilization occurs) to the leachates by the disposal media. The leaching properties of the media also give a basis for comparison of leachates derived from FBC wastes to leachates derived from natural earth materials. Section 7.0 then presents the findings of the investigation concerning the attenuation of FBC waste leachate by exposure to the disposal media.

The results of Section 4.0 to 7.0 are brought together in an overall assessment of the FBC waste suitability which appears in Section 8.0. Section 9.0 summarizes the results of the attempt to establish an empirical but rigorous statistical relationship between the lab and field results for both leachate generation and attenuation. Section 10.0 presents the results of the determination of the compatibility of typical landfill liner materials with FBC waste leachate. References are given in Section 11.0.

In general, the findings of the investigation are presented in summary form in this text. Extensive backup material, including procedural details and tabulated data are given in several appendices. These appendices are referenced extensively throughout the text of the report. They include the following:

A. Sources of FBC Waste and Disposal Media, Detailed Hydrologic Analysis, and Chemical Analytical Procedures

B. FBC Solid Waste and Disposal Media Physical Properties

C. Solids Composition of FBC Solid Waste and Disposal Media

D. Laboratory Leaching and Attenuation Behavior of FBC Wastes

E. Behavior of FBC Wastes Under Field Conditions

F. Compatability of Landfill Liner Materials with FBC Waste Leachate

G. Statistical Prediction of Field Leaching and Attenuation Behavior Based on Observed Laboratory Results

H. Quality Assurance and Control

I. Interpretation of Chemical Trends and Comparison of Leachate Composition with Water Quality Standards and Criteria

J. Data List for Leachate Analyses

3.0 INVESTIGATION PROCEDURE

As noted, the principal environmental concern of FBC waste is for the potential effect on hydrologic systems, primarily on the water quality of surface-water and groundwater resources. Thus, the thrust of this investigation is on the chemistry and water quality of leachate that may be generated from future FBC waste landfills. Most of the components of the investigation were oriented toward determining leachate chemistry or were performed to obtain information needed to interpret the observed leachate characteristics.

Based on a survey of previous investigations of FBC solid waste and on preliminary studies for this program, several chemical species were selected as candidates for analysis. These parameters are shown in Table 3-1. Not all parameters were included in all components of the program. Analyses for most of the cations were performed by inductively coupled argon plasma emission spectrometry (ICAPES) and by atomic absorption spectrophotometry (AAS). Additional information on the chemical parameters analyzed and the methods of analysis is given below (Section 3.7).

TABLE 3-1. LIST OF CHEMICAL SPECIES INCLUDED IN CHEMICAL ANALYSIS

Aluminum	Iron	Silver
Arsenic	Lead	Sodium
Barium	Lithium	Specific Conductance
Beryllium	Magnesium	Strontium
Boron	Manganese	Sulfate
Cadmium	Mercury	Titanium
Calcium	Molybdenum	Total Dissolved Solids
Chloride	Nickel	Total Inorganic Carbon
Chromium	pH	Total Organic Carbon
Cobalt	Potassium	Uranium
Copper	Selenium	Vanadium
Fluoride	Silicon	Zinc

A multifaceted program of laboratory and field studies was undertaken to characterize the FBC wastes and their leachates. Representative samples of FBC wastes and natural geologic substrate materials (referred to in this report as "disposal media") were obtained in the initial stages of the program. The central component of the laboratory studies was a six-step sequential batch equilibration protocol for generating leachate from FBC wastes and for exposing the leachate to samples of disposal media.

The most important part of the field studies was the installation and operation of several large "field cells" which are intended to simulate the behavior of FBC wastes in a landfill disposal setting. These field cells were constructed with layers of waste and disposal medium and with sampling points to allow leachate to be collected after generation and after exposure to the layer of disposal medium.

As noted, the laboratory protocol was developed as a possible laboratory test which could be used to predict the behavior of FBC wastes under landfill conditions in the field. The rigorous statistical methods used to assess the value of the protocol as a predictor of field behavior is described below, and the results are given in Section 9.0.

All laboratory analyses were performed at Radian Corporation laboratories in Austin, Texas. The field cells were emplaced at the former EPA Mine Drainage Control Facility near Crown, West Virginia (approximately nine miles south of Morgantown).

Besides the laboratory protocol and field cells, several other lab and field investigations were performed. An overview of the principal elements of the program is given in succeeding paragraphs of this chapter. Details of the specific procedures used and the results of the analyses are given in the appendices.

3.1 Sources of FBC Waste and Disposal Media

Two criteria were used to identify suitable sources of FBC waste and disposal media. First, the material acquired was to be representative of future disposal situations that will be encountered when FBC becomes commercially viable. Thus, the waste was to be as similar as possible to future FBC waste streams from commercial units. The disposal media were to be representative of conditions that are likely to be encountered at future disposal sites. The second criterion was the availability of a sufficient quantity of waste and medium for the laboratory and field studies.

3.1.1 Waste Sources

Fluidized bed combustion units can be operated at either atmospheric pressure (atmospheric FBC or AFBC) or elevated pressure (pressurized FBC or PFBC). The feedstocks, processing, and test units are different for AFBC and PFBC. Whereas the combustion efficiency of single-stage PFBC operation is adequate, AFBC efficiency is usually increased by operating in a recycle mode, where the carryover material is collected and reinjected into the main beds. An earlier method of increasing AFBC efficiency, through the use of a carbon burnup cell, is no longer considered technologically competitive with the recycle method. Originally, this program was to include waste from an AFBC unit using a carbon burnup cell, but a second AFBC-with-recycle waste was chosen instead.

The following three pilot plants were selected as waste sources on the basis of mode of operation and representation of waste generated at future commercial FBC operations:

- PFBC: Exxon Miniplant, Linden, NJ;
- AFBC: EPRI/B&W* 6' x 6' unit, Alliance, OH; and
- AFBC: Georgetown University Boiler, Washington, DC.

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*EPRI/B&W: Electric Power Research Institute/Babcock and Wilcox.

These waste sources are referred to as Exxon PFBC, Alliance AFBC and Georgetown AFBC respectively in this report. Additional details on the feedstocks, operating conditions, and ratios of waste streams from different parts of these three plants are given in Appendix A.

3.1.2 Disposal Media Sources

A suite of geologic materials was identified and acquired to evaluate how leachate composition is affected when the leachate is exposed to typical substrate material of a landfill. These "disposal media" were obtained from areas which are typical of future disposal site conditions. The materials were also selected to represent a broad range of geochemical and hydrologic conditions. The six disposal media selected were shale, coal seam interburden, sandstone, glacial till, alluvium, and limestone.

The shale, sandstone, till, and alluvium are widely occurring surface or near-surface materials. They include a general range of fine-grained (less permeable) to coarse-grained (more permeable) materials, they have typical mineralogical compositions, and they represent both consolidated and unconsolidated strata. The limestone and interburden provide alkaline and acidic geochemical extremes, respectively, and they also simulate disposal in a limestone quarry or a coal mine. These six media are thus representative of typical FBC disposal site substrates.

The disposal media were acquired from the nearest available sources to the Crown, West Virginia field site because the greatest quantity of material was required for the field cells. The sources of the disposal media are summarized in Table 3-2; additional details are given in Appendix A.

3.2 Laboratory Batch Equilibration Protocol

The fundamental component of the laboratory studies was a series of batch equilibration experiments ("shake tests") which were conducted according to a rigorous protocol. This protocol consists of six related steps. The first three steps are designed to characterize the leaching behavior of a single waste, and the last three steps assess changes in waste leachate composition resulting from exposure to a single disposal medium.

TABLE 3-2. SOURCES OF DISPOSAL MEDIA

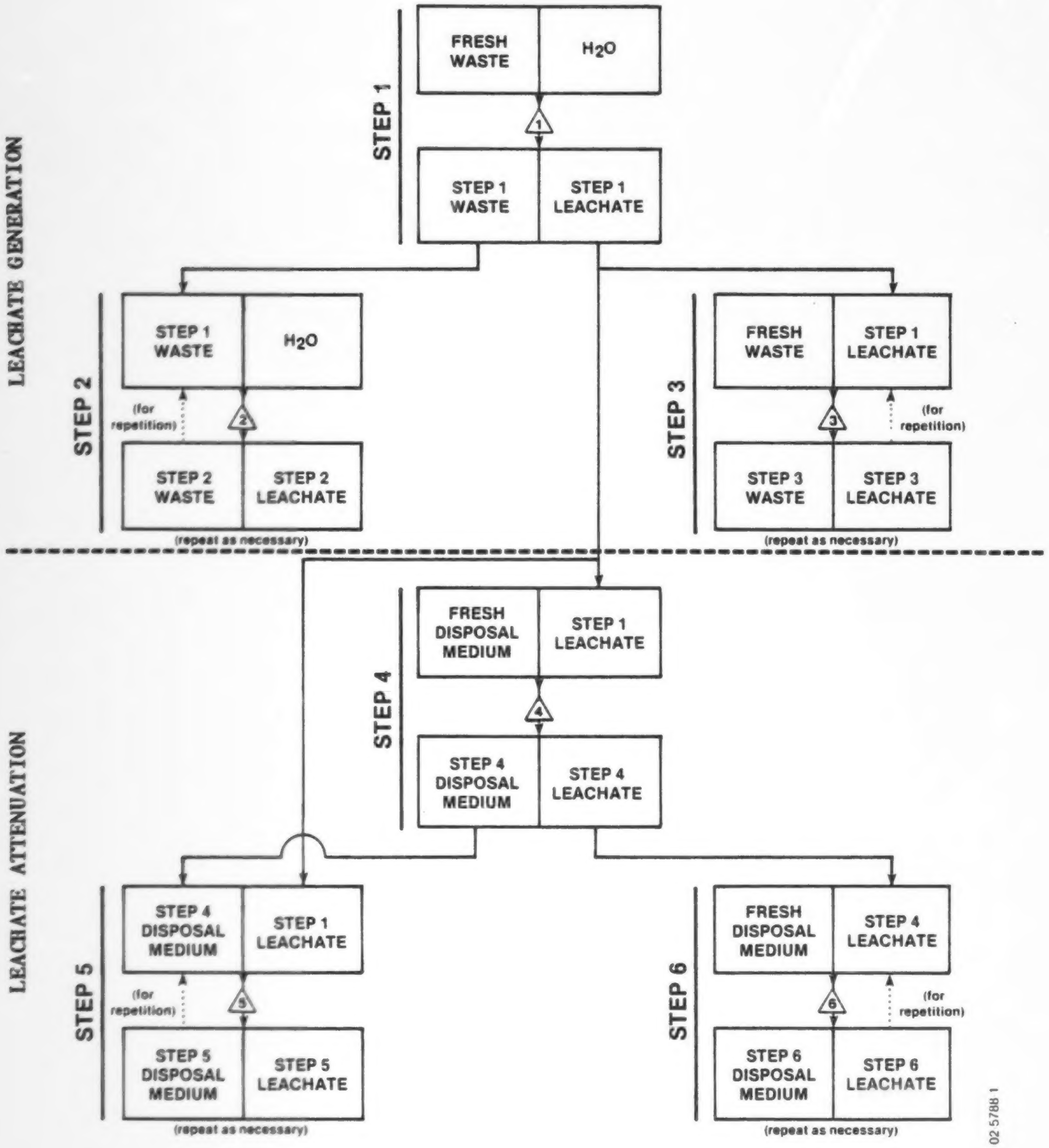
Medium	Formation (Age)	Description of Source
Shale	Cassville Shale Member of Dunkard Group (Permian)	Christopher No. 3 Coal Mine, Monongalia County, West Virginia
Interburden	Shale Parting in Waynesburg Coal (Upper Pennsylvanian)	Christopher No. 3 Coal Mine, Monongalia County, West Virginia
Sandstone	Waynesburg Sandstone of Dunkard Group (Permian)	Christopher No. 3 Coal Mine, Monongalia County, West Virginia
Glacial Till	Ground Moraine from Wisconsin Glaciation (Quaternary)	Excavation in Union County, Ohio
Alluvium	Ohio River Valley Floodplain Deposit (Quaternary/Recent)	Stockpiled Overburden at a Sand and Gravel Pit, Washington County, Ohio
Limestone	Greenbrier Limestone (Mississippian)	Greer Limestone Company, Monongalia County, West Virginia

3.2.1 Protocol Steps

The relationship of the six steps of the batch equilibration protocol is shown in Figure 3-1. Each step is summarized below; the protocol is described in detail in Appendix D.

3.2.1.1 Protocol Step 1--Initial Leaching

In the first step of the protocol, the waste was leached with deionized water to measure primary or initial leaching. No pH control was used. The solid and liquid phases were equilibrated for one day, two days, and seven days to define the rate and extent of leaching. Only 7-day leachates or



LEACHATE GENERATION
LEACHATE ATTENUATION
STEP 1
FRESH WASTE
H2O
1
STEP 1 WASTE
STEP 1 LEACHATE
STEP 2
STEP 1 WASTE
H2O
(for repetition)
2
STEP 2 WASTE
STEP 2 LEACHATE
(repeat as necessary)
STEP 3
FRESH WASTE
STEP 1 LEACHATE
3
(for repetition)
STEP 3 WASTE
STEP 3 LEACHATE
(repeat as necessary)
STEP 4
FRESH DISPOSAL MEDIUM
STEP 1 LEACHATE
4
STEP 4 DISPOSAL MEDIUM
STEP 4 LEACHATE
STEP 5
STEP 4 DISPOSAL MEDIUM
STEP 1 LEACHATE
(for repetition)
5
STEP 5 DISPOSAL MEDIUM
STEP 5 LEACHATE
(repeat as necessary)
STEP 6
FRESH DISPOSAL MEDIUM
STEP 4 LEACHATE
6
(for repetition)
STEP 6 DISPOSAL MEDIUM
STEP 6 LEACHATE
(repeat as necessary)
02 5788 1

Figure 3-1. Multi-Step Laboratory Leaching Protocol.

leached solids were carried forward to succeeding steps. After the required equilibration period, the solid and liquid phases were separated. The leachates were analyzed or carried forward to Steps 3, 4, or 5. The solids were carried forward to Step 2 or discarded.

3.2.1.2 Protocol Step 2--Secondary Leaching with Eluant Replacement

Solids that were initially leached for seven days in Step 1 were subjected to additional leaching by fresh eluant (deionized water). This step was designed to correspond with leaching behavior in field conditions when infiltrating water continues to pass through solid residues after initial leaching. Step 2 leachates were generally equilibrated for seven days.

After the equilibration period, the solid and liquid phases were separated. The leachates were analyzed, and the solids were carried forward for repetition of the step. The process was repeated several times in an attempt to reach a condition in which no significant additional leaching occurred when fresh eluant was placed upon previously leached waste. After the equilibration period of the final repetition of Step 2, samples of the residual solids were analyzed.

3.2.1.3 Protocol Step 3--Secondary Leaching with Waste Replacement

Leachate that had been initially equilibrated for seven days in Step 1 was placed in contact with fresh (unleached) waste. This step was designed to measure the extent to which leachate will continue to become more concentrated as it percolates and encounters additional waste under field conditions. This step also allowed determination of whether or not a given species is in a condition of saturation with regard to secondary leaching. Step 3 leachates were generally equilibrated for seven days.

3.2.1.4 Protocol Step 4--Initial Attenuation by a Disposal Medium

Although "attenuation" in the strict sense connotes a reduction in concentration, the term is used here for brevity to describe all the chemical changes in the leachate resulting from exposure to the disposal media, including mobilization. The combined term attenuation/mobilization is used extensively in the appendices.

In Step 4, leachate that was initially equilibrated for seven days in Step 1 was placed in contact with a disposal medium for one, two, and seven days. This step was designed to assess the attenuating capacity of (or contaminant mobilization from) a given medium and to allow comparisons to be made among the six different media. Analysis of the leachate at the three time intervals was intended to examine the effects of time of leachate exposure on attenuation or mobilization.

In Step 4, 12 samples at a time were usually set up for seven day exposure to the disposal medium. After the required equilibration period, the solid and liquid phases were separated. Two of the leachates produced were set aside for analysis. The remaining leachates were composited and carried forward to Step 6. The leached solids were carried forward to Step 5 or discarded. Step 4 leachate was generated six times during performance of the leaching protocol, once for each of the six disposal media.

3.2.1.5 Protocol Step 5: Repeated Exposure of Disposal Media to Fresh Leachate

Disposal media from Step 4 that were previously in contact with Step 1 leachate for seven days were placed in contact with additional leachate from Step 1. This step was designed to assess the capacity of the disposal media to bring about additional attenuation when in contact with fresh leachate, such as would occur with continued infiltration of leachate into the substrate below a landfill.

Step 5 leachates were set up in duplicate for each disposal medium. After the equilibration period, the solid and liquid phases were separated. The two leachates were set aside for analysis, and the solids were carried forward for repetition of the step. This process was repeated several times in an attempt to reach the point where no significant attenuation occurred when Step 1 leachate was placed on previously leached disposal medium. After the final repetition of Step 5, the final two leachates and the burdened disposal media were analyzed.

3.2.1.6 Protocol Step 6: Repeated Exposure of Leachate to Fresh Disposal Media

Leachates that had been initially equilibrated for seven days in Step 4 and that contained residual concentrations of key species following initial attenuation were placed in contact with unleached disposal media. This step was designed to determine incremental (secondary) attenuation that could occur as leachate infiltrates substrate materials that have not been previously exposed to leachate.

To repeat Step 6, sufficient samples were set up initially to provide the necessary eluant for the desired number of repetitions. At the end of each repetition, the solid and liquid phases were separated. The leachates from two samples were analyzed, and the remaining leachates were composited to provide the eluant for the next repetition with fresh medium. The disposal media used in this step were discarded.

3.2.2 "Fixed" Variables of the Protocol

Based on the results of leaching test procedures found in the literature and on the findings of preliminary studies for this program, several variables were fixed as follows:

- The initial (Step 1) extracting liquid phase (eluant) was deionized water;
- The extraction times were one day, two days, and seven days;

- The solid-to-liquid mass ratio was 1:10 (25g:250mL liquid) in order to minimize solubility limiting effects as well as common ion and solution nonideality effects for species of interest;

- All wastes and disposal media were ground to obtain uniform particle size to ensure homogeneity of wastes and reproducibility;

- Continuous solid and liquid agitation was maintained on a rotator at constant specified parameters to maximize liquid-solid contact with minimum particle abrasion; and

- The containers were air tight, so no carbon dioxide exchange with the atmosphere occurred during agitation.

It is recognized that grinding the wastes increased the surface area exposed to the eluant and possibly exposed different material in the interior of the original particles than was present on the particle surfaces. The effect of sample grinding was investigated and is described below. The Rugged Rotator, Model RD-250 (manufactured by Kraft Apparatus, Inc.) was selected because it permits good eluant-solid contact without such vigorous agitation as to cause abrasion of the solids. The incline of the head of the rotator was adjusted to an angle of about 70° to the horizontal so that there was end-over-end action of the leachate within the container. The speed of rotation was set at about six rpm.

3.2.3 Preparation of Waste and Disposal Media for the Protocol

The waste and disposal media samples were prepared to ensure representativeness and reproducibility. For each sample type, sufficient sample was prepared initially for carrying through all steps of the protocol; approximately 10 kg of waste and one kg of each disposal medium were required. The solids preparation procedure consisted of coning and quartering, crushing, drying, grinding, and mixing steps. After coning and quartering by ASTM methods to obtain a representative sample, the samples were crushed to a small enough size to fit into a grinder. Before grinding, the samples were dried at 50°C for 24 hours. The solids were ground to approximately 100-200 mesh and mixed to obtain a homogeneous sample.

3.2.4 Sample Flow Through the Protocol

The sample containers used on the agitator have a volume of 250 mL. To maintain the stipulated 1:10 solid/liquid ratio, 25 g of solid were weighed and transferred to the container, and deionized water was added to fill the container. The containers were then mounted in the agitator and rotated for the stipulated time for the sample (one, two, or seven days).

After the equilibration period, the solid and liquid phases were separated, and one or both of the phases were preserved as appropriate for analysis. Phase separation was accomplished with a high-speed centrifuge or by filtering with a 0.4 micron filter. The liquid phase (leachate) was split into four aliquots, individually preserved, and analyzed. The solid phase, when a solids analysis was scheduled, was oven-dried at 50°C overnight, ground with mortar and pestle, and stored in a clean container until digested and analyzed.

3.3 Field Cells

The principal component of the field studies was the design, installation, and operation of 13 large, cylindrical, hydrologically isolated field cells which contained layers of waste and disposal media. The objective of the field cells was to provide data on the generation and attenuation of leachate from various combinations of FBC wastes and disposal media under "quasi-field" landfill conditions. Although landfill operators usually provide for waste compaction, the field cells were not compacted in order to achieve "accelerated" leachate generation and attenuation conditions, although the degree of acceleration was not quantifiable. It was also necessary to leave the wastes uncompacted to be sure that leachates would be obtained during the timeframe of the experiment. The installation and operation of the field cells are summarized here; details are presented in Appendix E.

The field cells were large-diameter disturbed-media lysimeters which simulated FBC landfills as closely as practicable. They were conceived as a logical bridge between laboratory batch equilibration tests and a full-scale, operating disposal facility. The major differences from laboratory conditions included unsaturated flow with varying moisture content, intermittent input from natural precipitation, temperature fluctuation, particle size of the waste and disposal media, and availability of atmospheric carbon dioxide. The primary product of the field cell studies was a series of observations (throughput volumes and chemical analyses of samples) over time which reflected the effects of a natural climatic pattern on representative waste disposal systems.

The site selected for the construction and operation of the field cells was the former EPA Mine Drainage Control field site near Crown (unincorporated), West Virginia. The site is in a small valley which is roughly 1,000 feet[1] in elevation. The climate of the Crown site is "humid continental", with severe winters, moderately hot summers, and precipitation evenly distributed throughout the year. The annual mean precipitation is about 42.5 inches and the average annual pan evaporation is approximately 28.4 inches.

A total of 18 field cells was initially constructed, but 5 of the cells were not used because of the decision not to study AFBC waste from units using the carbon burnup cell mode of operation (Section 2.1.1). Field cells for the Georgetown AFBC wastes were not constructed. The test matrix for the field cells is shown in Table 3-3. This matrix includes two control cells containing disposal media only.

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[1] English units are used in this report where they are the commonly used units for the data presented. A summary conclusion table for English to metric units is given at the end of this report.

TABLE 3-3. TEST MATRIX FOR FIELD CELLS AT CROWN, WEST VIRGINIA

Disposal Medium	Control Cell	Exxon PFBC waste	Alliance AFBC waste	Total Cells
Shale	1	2	1	4
Interburden	–	–	1	1
Sandstone	–	1	–	1
Glacial Till	–	1	–	1
Alluvium	1	1	2	4
Limestone	–	1	1	2
TOTALS	2	6	5	13

3.3.1 Field Cell Design and Construction

The containers used for the field cells were the largest readily available size of reinforced concrete pipe, which was eight feet long and 48 inches in diameter. The intent in choosing this large size was twofold: 1) to ensure sufficient size that field simulations were satisfied with reasonable construction and waste requirements; and 2) to minimize "wall effects" and reduce the impact of inadvertent segregation of waste and disposal media during emplacement. The 48-inch diameter provided a significant increase over common laboratory scale. A typical large laboratory column might be as much as eight inches in diameter; the field cells had a cross-sectional area 36 times as large.

The geometry of individual field cells and the layout of the cells are shown in Figure 3-2. The overall geometry of each field cell was a 1.5-foot layer of waste emplaced over a three-foot layer of disposal media. Above the waste was another layer of disposal medium that was one foot thick. The mass of the waste and disposal medium in each cell is shown in Table 3-4. The 18 field cells were erected in three rings of six. Within each ring was a seventh six-foot diameter central cylinder, which served as an equipment shelter and provided access for sampling.

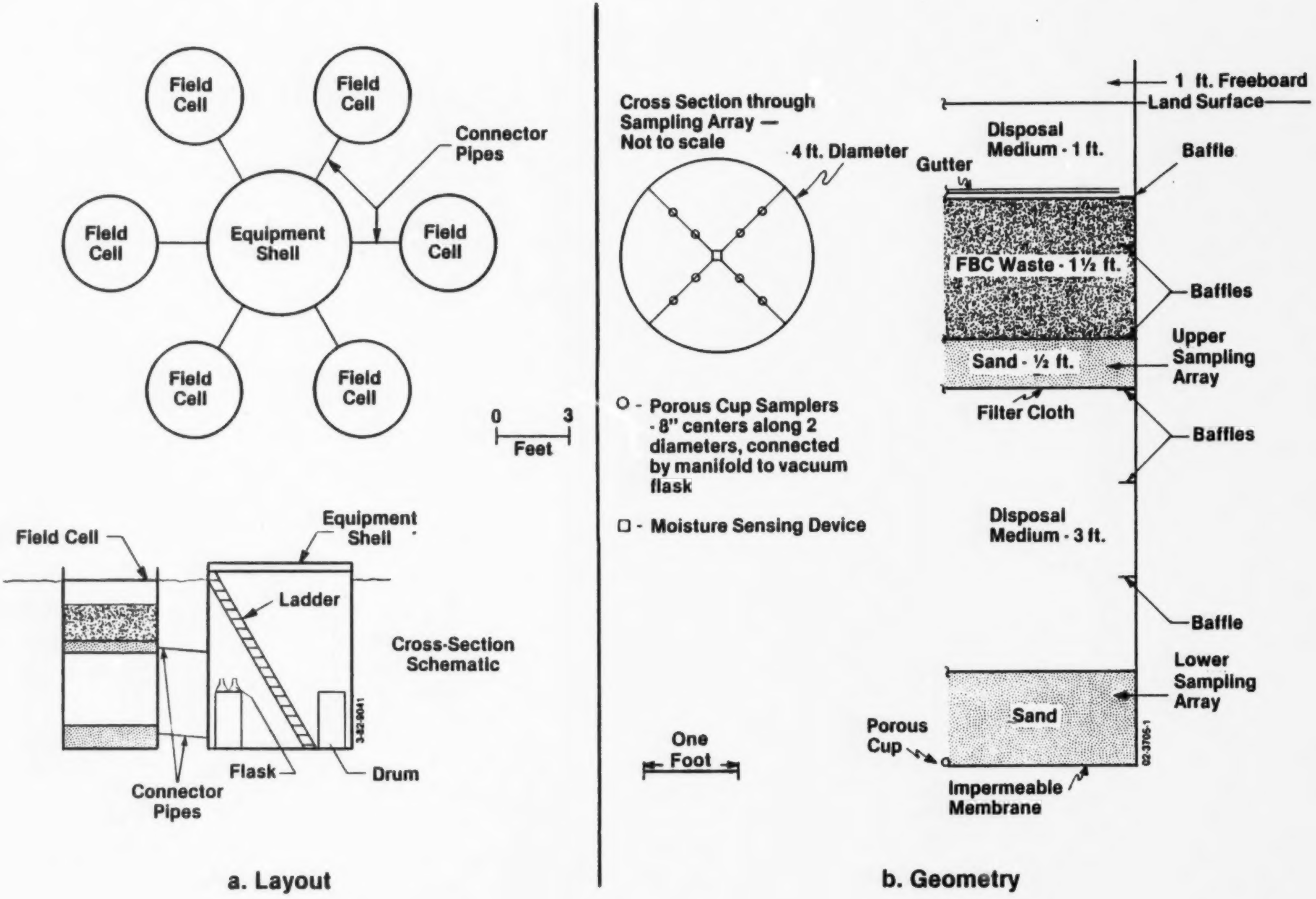
Field Cell
Field Cell
Connector Pipes
Field Cell
Equipment Shell
Field Cell
Field Cell
Field Cell
0
3
Feet
Field Cell
Equipment Shell
Ladder
Cross-Section Schematic
3-82-9041
Flask
Drum
Connector Pipes
a. Layout
Cross Section through Sampling Array — Not to scale
4 ft. Diameter
O - Porous Cup Samplers - 8" centers along 2 diameters, connected by manifold to vacuum flask
□ - Moisture Sensing Device
One Foot
1 ft. Freeboard
Land Surface
Disposal Medium - 1 ft.
Gutter
Baffle
FBC Waste - 1½ ft.
Baffles
Sand - ½ ft.
Upper Sampling Array
Filter Cloth
Baffles
Disposal Medium - 3 ft.
Baffle
Lower Sampling Array
Sand
Porous Cup
02-3705-1
Impermeable Membrane
b. Geometry

Figure 3-2 Field Cell Layout and Geometry.

TABLE 3-4. CONTENTS OF FIELD CELLS

Field Cell Number	Waste	Disposal Medium	Mass of Waste (10^6g)	Mass of Disposal Medium (10^6g)
1	Exxon PFBC	Shale	0.8	1.7
2	Exxon PFBC	Shale	0.8	1.7
3	Exxon PFBC	Till	0.8	1.2
4	Exxon PFBC	Limestone	0.8	1.8
5	Exxon PFBC	Alluvium	0.8	1.8
6	Exxon PFBC	Sandstone	0.8	1.8
7	None (control)	Shale	N/A	3.3
8	NF[1]	Sandstone	-	1.8
9	NF	Alluvium	-	1.8
10	NF	Interburden	-	1.4
11	NF	Till	-	1.2
12	None (control)	Alluvium	N/A	3.0
13	Alliance AFBC	Interburden	0.8	1.4
14	Alliance AFBC	Alluvium	0.8	1.8
15	Alliance AFBC	Alluvium	0.8	1.8
16	Alliance AFBC	Limestone	0.8	1.8
17	Alliance AFBC	Shale	0.8	1.7
18	None (spare cell)	None	N/A	N/A

[1] NF = Not filled because AFBC wastes from units using the carbon burnup cell mode of operation were not studied.
N/A = Not applicable.
Average mass/cell = 2.6 x 10^6g

The field cells were designed for hydrologic isolation and for minimum exposure of leachate to the concrete cylinders. The bases of the cells were sealed using synthetic liner material, and the inside surfaces of the concrete cylinders were painted with epoxy. The problem of "short-circuiting" of flow along the walls was addressed in the design of the field cells by incorporating circumferential baffles which were cemented to the interior walls of the field cells.

Layers of inert silica sand were incorporated in the field cell design for collection of leachate samples and to allow the cells to operate in hydrologic isolation. The sand layer below the waste body was used to draw off leachate samples prior to any contact with the underlying disposal medium. Below the disposal medium was a dual purpose sand layer. This layer contained the lower sampling array from which leachate samples were extracted after exposure to the lower disposal medium. In addition, a single large porous ceramic cup (filter candle) was installed at the base of the cell and maintained at a constant tension to prevent saturation of the field cell, which allowed the cell to be operated in hydrologic isolation. The volume of the leachate collected from the filter candle was measured so that the throughput of the cell could be determined.

3.3.2 Field Cell Operation

The field cells were initially irrigated with deionized water to field capacity and thereafter exposed only to natural precipitation. One of the objectives of the experiment was to observe the consequences of exposure to natural rainfall. Infiltrating precipitation passed through the upper layer of disposal medium and then passed through the waste body, leaching soluble constituents from the disposal medium and waste. Inasmuch as the infiltrate then migrated from a fine-grained into a coarse-grained medium, the lower portion of the waste body probably became saturated and remained saturated, because of capillary action, during the full course of the experiment.

The field cells were completed and placed in operation as appropriate wastes became available. Cells 1 through 7 and Cell 12 (Exxon PFBC cells and control cells) were operated from August 1979 to December 1980. Cells 13 through 17 (Alliance AFBC cells) were operated from March 1980 to April 1981. Following these initial periods of operation, both sets of cells were subjected to an intensive sampling schedule from June through November 1981.

During sampling, a 500 mL sample was collected at each sample point (upper and lower) for chemical analysis. Each sample was split, preserved, and shipped to Radian laboratories for analysis.

The volume of flow of water through the cells was measured and recorded as input and output. Precipitation input to the cells was monitored by a recording rain gage installed on-site. The supplemental irrigation that was applied to bring the cells to field capacity was metered. The throughput removed by the filter candle in the base of each cell was accumulated in a

30-gallon drum (one per cell) in the central equipment shelter of each field cell array. These drums were pumped out periodically, and the accumulated volume was measured. The volume in the drum, plus quantities removed by the sample arrays, was recorded as cell throughput.

The specific sampling procedures in the field consisted of the following steps:

- Vacuum (0.3 atmosphere) was applied to each sample array (upper and lower sample point) and maintained until a precipitation event occurred;
- Each drum was pumped out, and the quantity of throughput (leachate) was measured and recorded;
- The racks containing the vacuum flasks were removed for breakdown; the volume in each vacuum flask was recorded, and the contents of the two flasks servicing a single sample point were composited;
- The pH and specific conductance of each sample were measured, and the sample was split and preserved according to a written protocol;
- Vacuum was reapplied to the drums, the vacuum flask racks were reassembled but not connected to vacuum, and the site was closed and locked;
- Samples were cooled and shipped to Radian's laboratories in Austin for analysis; and
- At monthly intervals, the chart and batteries for the recording rain gage were changed.

3.4 Landfill Liner Study

Although the bulk of FBC waste that will be produced at future commercial plants probably will be nonhazardous, it is possible that some waste will be classified as hazardous under the provisions of the Resource Conservation and Recovery Act and pursuant regulations. Waste that is classed as hazardous will have to be disposed of in a facility that provides hydrologic isolation of the waste. Liner materials, including natural clay and synthetic membranes, are commonly used to ensure hydrologic isolation of landfills. As noted, some nonhazardous waste landfills may also employ liner materials for groundwater protection in certain disposal settings.

Historically, synthetic liners have provided an economical method of leachate and fluid waste containment with minimal permeation. They are generally relatively simple to install and maintain. Their major disadvantages are potential breakdown due to chemical interaction with contained wastes, physical changes (cracking, stretching) with temperature change, and susceptibility to laceration and punctures. Clay liners have been used extensively in large-area waste management facilities, sometimes in conjunction with synthetic membrane liners.

An investigation was performed to measure the chemical compatibility of candidate landfill liners in continuous and intimate contact with FBC leachate and to determine the integrity (over 18 months) of the liners. The procedure of this investigation is described in detail in Appendix F. The landfill liners studied were:

- Neoprene;
- Polyvinyl chloride;
- Chlorinated polyethylene;
- Chlorosulfonated polyethylene (Hypalon);
- Butyl rubber;

- Ethylene propylene diene monomer (EPDM) rubber; and
- Sodium bentonite clay.

These liners were chosen because they are commonly used and they have been proposed as sanitary landfill liners in several previous studies of liner compatibility. They have been extensively studied for other types of wastes (industrial, utility, and other), and their relative merits for application have been analyzed in terms of cost, engineering, and availability.

The investigation of the organic-based liners involved exposing the liner materials to FBC waste leachate and monitoring the structural integrity of the liners and the organic content of the leachate. The six liners were placed in continuous contact with Step 1, seven day leachate from Exxon PFBC waste. Potential liner degredation was studied by monitoring three parameters: 1) tensile strength of the liner (ASTM, Method D-412); 2) liner surface characteristics as determined by scanning electron microscope (SEM) observation; and 3) total organic carbon (TOC) concentration in the leachate contacting the liner. Tensile strength and liner surface characteristics were also determined for each liner material prior to contact with leachate. Enough strips of each liner were placed in contact with leachate to allow three per month (for 18 months) to be removed for measurement of tensile strength (in triplicate) and for SEM observation. Samples were labeled for SEM observation such that the same approximate area was studied before and after leaching. Every month, an aliquot of the leachate was removed along the three liner strips and analyzed in duplicate for total organic carbon (TOC). The combination of these three tests was used to assess degradation of the organic-based liners over the 18 months of the investigation.

In order to investigate the potential for clay liner breakdown upon exposure to FBC waste leachate, clay lattice degradation was assessed by placing the sodium-exchanged Wyoming bentonite in continuous and intimate contact with PFBC waste leachate (by agitation), and observing the following: 1) physical changes in the clay particles as determined by SEM; 2) crystalline structure changes as determined by X-ray powder diffraction; and 3) aluminum concentration increases in the leachate. Each month aliquots of both the clay mineral and the leachate were taken and the above parameters determined. SEM and X-ray diffraction allowed direct observation of changes in the clay mineral structure, whereas an increase of aluminum concentration in the leachate was used to indicate if chemical attack of the clay lattice by the leachate had occurred.

3.5 Corollary Laboratory Studies

Besides the six-step laboratory protocol and the landfill liner study, several corollary and supportive investigations were performed in the lab. These corollary studies included the following:

- Physical characterization of the FBC wastes and disposal media;
- Chemical analysis of solid samples of wastes and disposal media;
- Determination of leachate composition in laboratory columns, some of which contained disposal media and some of which contained layers of waste and disposal medium;
- Limited laboratory protocol leaching (using deionized water as the eluant) of fresh disposal media and disposal media previously exposed to leachate;
- Limited laboratory protocol leaching of FBC waste with leachate derived from deionized water leaching of disposal media;
- Leaching of FBC wastes by the RCRA Extraction Procedure for toxicity; and
- Evaluation of several of the experimental procedures used in the laboratory study components.

The details of these studies are summarized below and reported in detail in Appendix D.

3.5.1 Physical Characteristics of FBC Wastes and Disposal Media

Several physical parameters of the FBC wastes and disposal media were determined; the physical parameters determined for the wastes were particle size distribution, specific surface area, specific gravity, and particle surface characteristics (by SEM). The same physical parameters were determined for the disposal media. In addition, the media were analyzed by binocular microscope examination of unconsolidated materials and polarizing microscope examination of thin sections of consolidated materials. The studies of the physical characteristics of the FBC wastes and disposal media are described in Appendix B.

3.5.2 Solid Sample Composition and Other Chemical Properties

As an aid to interpreting the observed leaching behavior of FBC wastes, the chemical composition of the solid samples was determined by sample digestion and analysis of the digest solution. Samples were prepared by one of the following methods: 1) lithium metaborate fusion; 2) perchloric acid digestion; 3) sodium carbonate fusion; and 4) nitric acid extraction. The solids composition of the disposal media was determined by the same methods that were used for the FBC wastes.

The composition of the FBC wastes was also studied by X-ray diffraction, X-ray fluorescence, and electron microprobe. In addition, ultimate and proximate analyses by ASTM methods were performed on the wastes. Most of the chemical properties determined for the wastes were obtained both for the fresh (unleached) and leached wastes.

The chemical and mineralogical compositions of the disposal media were determined principally by microscope examination and X-ray diffraction analysis. Most properties were determined both before and after exposure to

FBC leachate. The solid sample composition investigations are described in detail in Appendix C.

3.5.3 Laboratory Column Studies

Two types of column studies were performed in the laboratory: (1) control columns containing only disposal media, which were used as experimental controls for the field cells; and (2) small leaching columns, which contained both wastes and disposal media. These investigations are summarized in detail in Appendix D.

3.5.3.1 Laboratory Control Columns

The test matrix for field cells included two control cells containing disposal media only (Table 3-3). To supplement these two control cells, a complete set of control (media only) columns were constructed and operated in the laboratory. These columns were six inch diameter plexiglass cylinders, six feet long, containing a six inch lift of inert silica sand at the base and roughly five feet of disposal medium. The columns were mounted vertically in wall racks, and sample collection flasks were placed under each.

Dry media were poured (but not packed) into the columns, which was analogous to the filling procedures at the field cells. A single porous ceramic cup at the base served as both a bottom drain and a sample collection device. The laboratory columns were not fitted with baffles, but channeling was not observed through the clear plexiglas walls of the columns.

The laboratory columns were operated in parallel with the control cells in the field, but delayed by 54 days. Records of daily rainfall depths at the field site were converted to equivalent volumes, and each column was irrigated with that volume of deionized water. The porous ceramic cup at the base was kept under a constant 0.3 atmosphere tension to remove all leachate generated and to ensure unsaturated flow. Samples from the laboratory control columns were analyzed for the same parameters as the leachates from the control columns in the field.

3.5.3.2 Laboratory Leaching Columns

Five columns were constructed from three inch diameter plexiglas cylinders. Although some of these columns contained disposal media and thus experienced attenuation processes they are referred to here as "leaching" columns to distinguish them from the control columns described above. The leaching columns contained the following combinations of waste and disposal media:

- Sandstone over ground Alliance AFBC waste;
- Shale over ground Exxon PFBC waste;
- Shale over unground Exxon PFBC waste;
- Ground Alliance AFBC waste sandstone layers above and below; and
- Ground Exxon PFBC waste with shale layers above and below.

Deionized water was added to the columns at a rate designed to achieve the estimated residence time of leachate in the field cells. The leachates were analyzed for the same parameters as the field cell leachates.

3.5.4 Corollary Leaching Studies

Four types of corollary studies were performed during the development of the six-step protocol and to obtain data to aid in the interpretation of some of the protocol and field cell results:

- Leaching of fresh disposal media with deionized water;

- Leaching of FBC waste with leachate generated from disposal media;

- Deionized water leaching of disposal media previously exposed to FBC waste leachates; and

- Toxicity determination by performance of the Extraction Procedure set forth in regulations pursuant to the Resource Conservation and Recovery Act.

These studies are detailed in Appendix D.

3.5.4.1 Leaching of Disposal Media

As reported in Section 6.0 below, the analytical results from the laboratory protocol, the laboratory control columns, and the field cells indicated that the disposal media, rather than attenuating FBC leachate, in many cases contributed as much or more of some species to the leachate as the FBC waste did. Consequently, supplementary studies were conducted to provide data on the leaching characteristics of the disposal media in the laboratory protocol. These data were developed to aid in the interpretation of the protocol results in the same way that laboratory control column data supplement field cell results.

The leaching of the disposal media was accomplished according to Steps 1 and 2 of the laboratory protocol. Seven repetitions of Step 2 were performed to determine the extent of continuing mobilization of contaminants by additional leaching with deionized water.

3.5.4.2 Leaching of FBC Waste with Disposal Media Leachate

When it was found during initial data review that the disposal media in many cases released contaminants to leaching solutions at nearly the same extent as FBC wastes, the comparison of laboratory and field results was complicated by the presence of the upper layer of disposal medium in the field cells. In the field cells, FBC waste was being leached by solutions that had equilibrated with one foot of disposal media, whereas in the laboratory protocol the waste was being leached by deionized water.

Some of the leachate that was generated during Step 1 leaching studies of the disposal media was used as an eluant for subsequent leaching of fresh FBC waste according to Steps 1 and 2 of the protocol. The disposal media used for this investigation were shale and sandstone. The waste used was Alliance AFBC waste. Seven repetitions of Step 2 were performed, and the leached waste was subjected to X-ray diffraction and solids analysis. All leachings were performed for seven days. The leachates generated were analyzed for the same parameters as other leachates from the laboratory protocol.

3.5.4.3 Leaching of "Burdened" Disposal Media

During the development of the laboratory protocol, Step 5 was initially performed using deionized water for the repetitions rather than Step 1 leachate. The objective of this procedure was to evaluate to what extent disposal media that had been "burdened" with contaminants during Step 4 would release these contaminants if subsequently leached by clean water. This situation would be analogous to leaching the substrate below an FBC waste landfill, as, for example, with a rising water table.

Subsequently it was determined that information on the ability of a disposal medium to continue to remove contaminants upon repeated exposure to new leachate would also be of value for comparison to data on the release of contaminants of burdened disposal media when leached by the fresh water. Step 5 was therefore changed so that Step 1 leachate rather than deionized water was used. Nevertheless, important data were obtained during the initial runs which indicate the ability of disposal media to retain contaminants which had previously been removed from FBC waste leachate. The original Step 5 procedure was redesignated as "Step 7" when it was replaced by the new procedure.

3.5.4.4 RCRA Extraction Procedure

Regulations developed pursuant to the Resource Conservation and Recovery Act of 1976 specify procedures for determining if a waste is hazardous. The test for the toxicity category, called the Extraction Procedure (EP), was performed on unground samples of Exxon PFBC, Alliance AFBC, and Georgetown AFBC waste. The leachate generated by the EP was analyzed for the eight metallic elements specified in the procedure and for other parameters included in the laboratory protocol for this program as well.

3.5.5 Interpretive Laboratory Experiments

Several ancillary investigations were performed to gain insight into some of the observed experimental results, including evaluations of: 1) sample representativeness; 2) day-to-day analysis variation; 3) the effects of leachate sample filtration; and 4) the effects of sample grinding. These investigations are summarized below and described in detail in Appendix D.

3.5.5.1 Evaluation of Sample Representativeness, Variation in Sample Analysis, and the Effects of Filtration

During performance of the six-step laboratory leaching protocol, a considerable quantity of Step 1 leachate was required to perform all iterations of subsequent steps, but only 250 mL could be generated in each sample bottle because of the type of shake test apparatus used. Consequently, several different Step 1 leachate samples had to be generated for each waste. A standard ASTM sampling method (Method C-50) was used to obtain, by representative reduced sampling, the 25 g of waste used for each leachate sample generated.

A thorough analysis of the data set indicated that there may have been some variation in the analyses caused by variation in analytical instrument performance from day to day. Also, during performance of the laboratory protocol, analyses for metallic cations were made after centrifugation but without filtering the leachate in the case of the Exxon PFBC waste and the Alliance AFBC waste. In the case of the Georgetown AFBC waste, the samples were filtered prior to analysis.

A special experiment was performed to simultaneously evaluate the representativeness of the waste samples obtained, the possibility of instrument variation, and the effects of sample filtering. In this experiment, five sets of Alliance AFBC waste samples were prepared by sampling repeatedly from different parts of the bulk sample for each set. Each of the five sets was thoroughly homogenized and divided into four components. One of the components was subjected to solids analysis and one was used for determination of physical properties.

The remaining two components were subjected to Step 1, seven-day extractions. Some of the leachates were analyzed directly and some were composited before analysis. The leachates from the extractions were analyzed in groups on different days. Some of the leachates were split and one of the splits was analyzed without filtering and one was filtered before analysis. The procedure was thus set up as a factorial design experiment to evaluate several aspects of the laboratory methods used. The general findings of this experiment was that the sampling procedure used was valid, there was little variation in instrument performance, and sample filtering had little effect on the analytical results. These findings are elaborated in Appendix D.

3.5.5.2 Evaluation of the Effects of Sample Grinding

In order to simulate a landfill in field conditions as closely as possible, the field cells were constructed by mixing the waste streams in the ratio of production, hydrating the wastes to a moist condition, and emplacing them in the cells. As noted, the waste preparation procedures for the laboratory were quite different; to ensure homogeneity and reproducibility, the samples were ground before leaching.

Three studies were conducted to evaluate the effects of sample grinding. In the first study, both ground and unground samples of Exxon PFBC waste were subjected to Step 1 leaching, and the leachate concentrations of several species were compared. In the second study, both Step 1 and Step 2 extractions were performed on Georgetown AFBC wastes, and the analytical results were compared for several species. Finally, laboratory leaching columns containing ground and unground waste were used to assess the effect of sample grinding on Exxon PFBC waste leaching characteristics in lab column conditions.

It was found in the first study that higher concentrations were observed for the unground than for the ground waste, which indicates that the grain size reduction may have resulted in re-adsorption of materials deposited on the outer surfaces of the grains. A statistical analysis of the results of the second study showed that grinding had very little effect on the leachate concentrations. Also, the laboratory leaching column study showed that grinding had little effect on leachate composition. Details of these findings are given in Appendix D.

3.6 Corollary Field Studies

Besides the field cell experiments described in Section 3.3, several corollary investigations were performed at the Crown, West Virginia field site. These studies are summarized here and described more completely in Appendix E.

3.6.1 Field Cell Coring

At the conclusion of the field cell experiments, cores were taken from six of the cells. These cores were taken for several purposes: 1) to assess changes in the consolidation, cementing, and physical appearance of the wastes after several months of leaching; 2) to obtain samples of the waste and disposal media for chemical analysis of the solids; and 3) to provide a means of obtaining a radiation profile of the radioactive tracers that had infiltrated the waste during a permeability study using radioactive chemical species (described below). Coring operations were undertaken at the field site using standard coring devices (Shelby tube and split-spoon sampler). The cores were described in the field, packaged, and returned to Radian laboratories for analysis.

3.6.2 Residence Time Study

During the initial stages of analysis of the chemical data from the field cells, the concentrations and trends as well as the pH of leachates were different from what was anticipated. Two hypotheses were advanced to explain what was felt to be incomplete interactions of the leachate with the waste mass. One hypothesis was the possibility of "armoring" of particles in the waste mass, during which surface hydration, leaching, and other reactions occurred on the outer portions of the particles. Once this "rind" of reacted material formed, the interiors of the particles would be protected from further reaction. It was also possible that the behavior was attributable to the availability of atmospheric carbon dioxide. Another hypothesis was that fractures formed in the unsaturated waste mass, which allowed fracture flow rather than intergranular flow to occur.

In an attempt to assess the type of flow through the field cells indirectly, a radiochemical study was performed on some of the cells to determine the residence time of the leachate in the cells. The procedure for this experiment was to apply a solution containing radioactive species on the top of the cells, follow the application with a large quantity of water, and then monitor the leachate collected from the upper and lower sampling points for the first appearance of the radioactive species. Four tracer species were chosen on the basis of half-life and "conservativeness" (degree of adsorption expected): Br-82, Ca-45, Sr-85, and Co-60.

The radioactive species did not appear in the leachates from the upper or lower sampling point during the time frame expected, so residence time could not be assessed directly. When the field cells were cored at the conclusion of the leachate collection period, the cores were returned to the lab for scanning to determine the depth of penetration of the longer-half-life species, but the type of flow occurring in the field cells could not be assessed.

3.6.3 Large Permeameter Study

During the development stages of the field program, it was realized that an important parameter to be considered when studying the problem of leachate generation from an FBC waste landfill was the type of permeability which would develop in the waste mass. For example, the leachate-generating properties of a mass of waste that was fully reacted to form a hard, impermeable monolith would be quite different from the properties of a mass which remained unconsolidated or became highly fractured.

An attempt was made to assess the permeability of uncompacted FBC waste and the change in permeability with time by constructing two large, cylindrical, above-ground permeameters containing Alliance AFBC and Georgetown AFBC waste. The cylinders were constructed above ground to maximize the effects of temperature fluctuation on secondary (fracture) permeability development. The permeability of the waste was measured initially after construction of the permeameters, again at an interim point, and finally at the conclusion of the field operations. The double ring method of permeability measurement was used for the experiment. The initial permeabilities of the wastes were quite similar and were comparable to a sandy loam soil. After several months of chemical changes and exposure to weathering processes, the wastes experienced a permeability reduction and were more comparable to silty clay soil.

3.7 Chemical Parameters Determined and Methods of Analysis

During the performance of the laboratory and field studies, a total of approximately 4500 samples were chemically analyzed. Table 3-5 shows a comprehensive list of the species and elements analyzed. For each parameter, the components of the lab and field studies for which the parameter was analyzed are indicated. A total of approximately 65,000 determinations were made during this investigation.

TABLE 3-5. SUMMARY OF CHEMICAL ANALYSES PERFORMED FOR THE MAJOR COMPONENTS OF THE PROGRAM

	Laboratory Studies								Field Studies		
		Six Step Main Protocol									
Element/ Species	Solids Composition	Exxon PFBC	Alliance AFBC	Georgetown AFBC	Disposal Media[1]	Control Columns[2]	Leaching Columns[3]	RCRA EP[4]	Exxon PFBC	Alliance AFBC	Control Columns
Ag	X	-	-	-	-	-	-	X	-	-	-
Al	X	X	X	X	X	X	X	-	X	X	X
As	-	X	-	-	-	-	-	X	-	-	X
B	X	X	X	X	X	X	X	X	X	X	X
Ba	X	X	X	X	X	X	X	-	X	X	X
Be	X	X	X	X	-	-	-	-	-	-	X
Ca	X	X	X	X	X	X	X	-	X	X	X
Cd	X	X	X	X	X	X	-	X	X	X	X
Cl	X	X	X	X	X	X	X	-	X	X	X
Co	X	X	X	X	X	X	X	-	X	X	X
Cr	X	X	X	X	X	X	X	X	X	X	X
Cu	X	X	X	X	X	X	X	-	X	X	X
F	X	X	X	X	X	X	X	-	X	X	X
Fe	X	X	X	X	X	X	X	-	X	X	X
Hg	-	X	-	-	-	-	-	X	-	-	X
K	X	X	X	X	X	X	X	-	X	X	X
Li	X	X	X	X	X	-	X	-	X	X	X
Mg	X	X	X	X	X	X	X	-	X	X	X
Mn	X	X	X	X	X	X	X	-	X	X	X
Mo	X	X	X	X	X	X	X	-	X	X	X
Na	X	X	X	X	X	X	-	-	X	X	X
Ni	X	X	X	X	X	X	-	-	X	X	X
Pb	-	X	-	-	-	-	-	X	-	-	X
pH	-	X	X	X	X	X	X	-	X	X	X
Se	-	X	-	-	-	-	-	X	-	-	X
Si	X	X	X	X	X	X	-	-	X	X	X
SO_4	X	X	X	X	X	X	X	-	X	X	X
Sp.Cond.	-	X	X	X	X	X	X	-	X	X	X
Sr	X	X	X	X	X	X	-	-	X	X	X
TDS	-	X	X	X	X	X	X	-	X	X	X
Ti	X	X	X	X	X	X	-	-	X	X	X
TIC	-	X	X	X	X	-	X	-	-	-	X
TOC	-	X	X	X	X	X	-	-	-	-	X
U	-	X	-	-	-	-	-	-	-	-	X
V	X	X	X	X	X	X	-	-	X	X	-
Zn	X	X	X	X	X	X	-	-	X	X	X

Note: Some species were not included in various parts of the program for several reasons. The principal reason was deletion of species in the latter analyses because of the findings in earlier analyses.

[1] Protocol Step 1 leaching of disposal media samples.

[2] Laboratory columns containing disposal media only, designed as controls for field cells.

[3] Laboratory columns containing wastes and disposal media.

[4] Extraction Procedure as stipulated by EPA regulations developed pursuant to the Resource Conservation and Recovery Act.

Most of the metallic ions were determined very cost-effectively with a multi-element analytical instrument, the inductively coupled argon plasma emission spectrometer (ICAPES). Several elements for which the detection limit was too high on the ICAPES were analyzed by atomic absorption spectrophotometry (AAS). Fluoride and pH were determined by selective ion electrode and glass electrode respectively. Specific conductance was measured by conductivity meter, and total dissolved solids was determined gravimetrically by filtering, drying, and weighing the residue from a carefully measured volume of sample. Sulfate and chloride were analyzed by ion chromatography. Total organic carbon was determined by an instrument specifically designed for that purpose. The methods of chemical analysis are described in detail in Appendix A.

3.8 Data Management System

Because of the large amount of data generated for this program, a sophisticated data management system was used to store the data, for performing statistical operations on the data, and for generating interpretive plots and diagrams. The data management system selected was the SAS software system (Reference 6) using an IBM 3033 computer and direct-access disk storage.

Because of its flexibility and wide variety of capabilities, SAS fulfilled all of the program's software needs. Data base management capabilities which were utilized included: 1) setup of new data files on the disk; 2) access to existing data files; 3) addition of new observations to existing data sets; and 4) merging of different data sets on the basis of common variables. The SAS system also includes a variety of statistical analysis capabilities, such as correlation and regression analysis, which were used in the project. The SAS system and the data base contained in the system are presented in Appendix J.

3.8.1 Laboratory Batch Equilibration Test Data Base

The chemistry data from the batch equilibration studies were received in sets separately from three sources--ICAPES elemental analyses, AAS elemental analyses, and all other chemical analyses. The chemistry data were stored with necessary codes so that different chemical analyses from the same equilibration test could be merged. This information included a code for leachate versus disposal medium sample, laboratory step number, leaching time in days, waste type, disposal medium, and a code indicating which of two or more replicate performances of a particular equilibration test the sample was from. More information on the codes of samples from the batch equilibration test is given in Appendices D and J.

Each time a set of data was received (for example, a set of ICAPES analyses for batch equilibration tests), it was stored on the computer with the necessary identifying information so that it could later be combined with other types of information for the same batch equilibration tests. Thus, it was not necessary to wait until the data for a batch equilibration test were complete to edit or begin to analyze the data which were available.

3.8.2 Field Cell and Laboratory Column Data Base

For the field cells, data were received separately for ICAPES elemental analyses, AAS elemental analyses, other chemical analyses, flow-through volume, and rainfall. Each time a set of data was received, it was stored along with the codes for the field cells, the sampling point (upper or lower) and the date that the sample was collected.

The rainfall data, which were stored in a separate file on the computer, were recorded as depth in millimeters on each day. The volumes of leachate from the upper collection point, the lower collection point, and the bottom of the field cell were recorded each time a leachate sample for chemical analysis was collected from a field cell. These data were also stored in a separate file in the computer and were used to determine flow-through volumes for each field cell. The same approach was used for the laboratory control columns, which received the same input of deionized water in the laboratory as the field cells received from natural precipitation in the field. The throughput (leachate) volumes for the laboratory columns and field cells were sorted by date of collection and by field cell or laboratory column code.

3.8.3 Generation of Data Printouts and Interpretive Diagrams

The SAS system was also used to produce various data tables and plots as needed throughout the project. The capabilities of the system to produce formatted output were used to produce the data list in Appendix J.

Additionally, tables and plots were produced as the basis for discussion and to present the results of analyses whenever needed. For example, computer-generated plots were used in Appendix D to show concentration trends with increasing leaching and with increasing attenuation in the laboratory protocol. In Appendix E, computer plots were used to show concentration trends of leachate from the field cells with time. Computer plots were also used to show the observed and corresponding predicted concentrations in the modeling discussion in Appendix G. In some instances, parts of the standard output from a statistical routine were transcribed manually from the computer output in order to present certain information in a precise form. The tables of regression coefficients and associated statistical measures presented in the modeling discussion in Appendix G are examples.

Also, the automatic data plotting and listing features of SAS were used throughout the project for inspection of raw data for quality control and other purposes.

3.9 Quality Control and Assurance

A comprehensive and rigorous quality control and quality assurance (QC/QA) element was included as an essential component of the program. The laboratory component of QC/QA efforts included regular calibration of instruments, analysis of spiked synthetic and leachate samples, analysis of standard samples of known concentrations to validate measurements, and replicate measurements. For the field studies, a test matrix including replicate field cells was prepared for QC/QA purposes. In addition, a complete set of control (media only) columns was operated in the laboratory with deionized water input equivalent to the rainfall experienced by the field cells. Also, two full-size control cells containing media only were operated at the field site. The laboratory control columns and field control cells also yielded data from leaching of disposal media which were useful for comparison with waste leachate data. The details of the QC/QA program are presented in Appendix H.

3.10 Modeling and Correlation

As noted, one of the objectives of the program of investigation was the development of a method of relating the results of the laboratory protocol to leachate generation and attenuation behavior in the field cells. If a rigorous relationship could be established between the lab results and field behavior, then FBC waste landfill behavior could be predicted on the basis of simple and inexpensive laboratory tests. The details of the attempt to establish this relationship are given in Appendix G.

Standard statistical techniques were employed in the attempt to establish an empirical but rigorous relationship between the lab and field results of this program. Two approaches, termed the "direct" and "indirect" methods, were used to establish the relationship. In the direct approach, polynomial fit techniques were employed to obtain a model of leachate concentration trends as a function of volume-per-mass ratio using lab batch equilibration data. This model was then first applied to the data from which it was derived to test the goodness of fit. Then, the model was tested on the field data to determine if the field results fit into the laboratory-derived model. The lab and field results from both the Exxon PFBC and Alliance AFBC studies were tested by the methods of the direct approach. This method, as described below, was relatively successful for relating lab and field results for leachate generation. It was less successful in relating the results for leachate attenuation.

The second approach differs from the first primarily in that the analytical results of several species were used to predict the concentration trend of each parameter. In this method, a regression model was first developed in which the concentration of a particular species is predicted in terms of the concentrations of other species in the preceding leaching step and possibly pH in the preceding or current leaching step. Subsequently, transformations are made through a set of mathematical steps to obtain models which predict concentration as a function of volume-per-mass ratio. Because this effort was only a feasibility study of the indirect method, only the Exxon PFBC waste leaching results were tested using the indirect approach.

3.11 Interpretation of Chemical Behavior

The major thrust of this program was on determining the composition of FBC waste, their leaching properties, and the attenuation characteristics of the leachate. The chemical and related data resulting from these studies are the principal results which are emphasized in this report. Many of the concentration ranges and trends observed reflected complex behavior involving numerous different chemical mechanisms. An attempt was made in Appendix I to advance possible chemical mechanisms which could account for the complex behavior observed. An evaluation was also made, by chemical equilibrium modelling, of the role of solubility control in leaching.

An overall assessment of the potential environmental acceptability of FBC wastes and their leachates was performed by making three comparisons: 1) chemical composition of FBC waste samples with similar composition of typical geological substrate materials; 2) composition of FBC waste leachates with leachates derived from geological materials; and 3) concentrations observed in FBC waste leachates with water quality standards and criteria.

4.0 FBC WASTE COMPOSITION AND PHYSICAL PROPERTIES

As noted in Section 3.0, the composition and physical properties of the FBC waste samples were determined by a variety of techniques. The solids composition was obtained by digestion and chemical analyses of the digest solution. The crystalline phases were analyzed by X-ray diffraction (XRD). There should be a relationship between the solids composition and the crystalline phases identified, although it must be recognized that the XRD method does not yield information on the amorphous component of the waste as the solids composition does. The relative quantities of crystalline and amorphous components of the FBC waste are not known. The principal physical properties examined were grain size distribution, particle surface characteristics, specific gravity, and specific surface area.

Generally, the composition and physical properties of the waste samples were determined both in the unleached condition and after leaching had taken place both in the laboratory batch equilibration protocol and in the field cells. The results of the analysis of the solids are presented in this section; the leaching behavior of the waste is described in Section 4.0.

4.1 Crystalline Phases in FBC Waste

X-ray diffraction was used to determine the crystalline phases present in the Exxon PFBC, Alliance AFBC, and Georgetown AFBC wastes. In addition, the crystalline phases present in a fourth waste from a small FBC unit at the EPA Industrial Environmental Research Laboratory (IERL) were assessed. The Exxon, Alliance, and Georgetown wastes were examined in fresh (unleached) condition and after leaching in Steps 1 and 2 of the laboratory protocol (described in Appendix A). The Exxon and Alliance wastes were also analyzed after leaching in the field cells. Wastes from the IERL FBC unit (at two operating temperatures) were examined. The details of the X-ray diffraction analyses are given in Appendix C.

4.1.1. Exxon PFBC Waste

As noted in Appendix A, the PFBC waste used for this program was composed of material from runs 79, 80, and 81 of the Exxon PFBC Miniplant. Both individual components (Cyclones 2 and 3) and composite samples of the Exxon PFBC waste were analyzed for crystalline composition. The crystalline components of wastes from Cyclone No. 2 (runs 79 and 80) were found to consist primarily of anhydrite ($CaSO_4$) and alpha-quartz (α-SiO_2) with some alpha-hematite (α-Fe_2O_3), magnetite (Fe_3O_4), dolomite ($CaMg(CO_3)_2$), and calcium silicate ($CaSiO_3$). The principal components of waste from Cyclone No. 3 (runs 80 and 81) were found to be anhydrite, quartz, and calcium silicate. Some $CaSO_4 \cdot 3MgSO_4$, hematite, dolomite, and magnetite were also found.

The major crystalline components of the unleached composite Exxon PFBC waste were anhydrite, periclase (MgO), and quartz. The predominant components of the composite waste after leaching in Step 1 and Step 2 (seven repetitions) of the lab protocol were gypsum ($CaSO_4 \cdot 2H_2O$), brucite ($Mg(OH)_2$), quartz, and calcite ($CaCO_3$).

Core samples were taken from three field cells (Cells 2, 3, and 5) containing Exxon PFBC waste at the end of the field leachate sampling program (see Appendix E). These core samples were subjected to X-ray diffraction analysis, and the major crystalline components were identified as ettringite ($Ca_{12}Al_3(SO_4,SiO_3,CO_3)_6(OH)_{12} \cdot 30H_2O$), gypsum, brucite, calcite, and quartz. Ettringite is a minor component of hydrated Portland cement and often occurs in blended mixtures of cured coal fly ash and sludge from SO_2 scrubbers of conventional power plants.

In summary, the unleached composite waste and the waste components (from the cyclones) were similar in that both contained principally anhydrite and alpha-quartz. The cyclone waste contained calcium silicate not observed in the composite waste, and the composite waste exhibited the presence of periclase not seen in either cyclone waste.

As expected, the principal effect of leaching was the apparent hydration of minerals observed in the unleached waste. Leaching in the laboratory protocol and in the field cells resulted in the formation of the hydrous minerals gypsum and brucite. Quartz was observed in both the leached and unleached waste. Calcite was found in the leached but not the unleached waste and was probably formed by reaction of atmospheric carbon dioxide with the waste and resulting precipitation of calcium carbonate. The calcite was apparently not derived from the sorbent material. The formation of ettringite by leaching in the field cells but not in the lab protocol is not easily explained but may attest to the more complex chemical conditions in natural disposal settings than in the protocol.

4.1.2 Alliance AFBC Waste

The crystalline components of unleached Alliance AFBC waste were determined first by analysis of a single sample and later in the program by analysis of five separate samples as part of a sample representativeness test (described in Section 3.5.5.1). The results of all of these analyses were consistent and showed the presence of anhydrite, portlandite ($Ca(OH)_2$), quartz, hematite, calcite and lime (CaO) in unleached waste.

After leaching in Step 1 and Step 2 (nine repetitions) of the lab protocol, the Alliance AFBC waste had crystalline components consisting of gypsum, portlandite, quartz, calcite, hematite, and ettringite. Core samples taken from three field cells containing Alliance AFBC waste (Cells 13, 14, and 17) were found to contain primarily portlandite, gypsum, and calcite with smaller amounts of quartz, ettringite, and hematite.

The principal effect of leaching on the Alliance AFBC waste again apparently was the hydration of several of the minerals observed in the unleached waste. The anhydrite and lime seen in the unleached waste did not appear in the leached waste. Likewise, the hydrous minerals gypsum and ettringite observed in the leached waste were not present in the unleached waste. Quartz, calcite, hematite, and portlandite were present in both the unleached and leached waste. There was no appreciable difference in the minerals observed in the leached waste from the lab protocol and the field cells.

Shake tests were performed on Alliance AFBC waste in which the eluant used was leachate from Step 1 leaching of disposal media rather than deionized water (Appendix D). X-ray diffraction analysis of the leached waste showed the presence of crystalline compounds that are similar to those in leached waste where deionized water was used. However, lime and anhydrite were also found, which indicates that not all hydration reactions went to completion when the disposal media leachate was used as the eluant.

4.1.3 Georgetown AFBC Waste

In the unleached condition, the Georgetown AFBC waste was found to consist of portlandite, anhydrite, quartz, calcite, lime, and hematite. After Step 1 and Step 2 (nine repetitions) leaching, the waste contained ettringite, gypsum, portlandite, anhydrite, quartz, hematite, and probably calcite. Thus the principal changes brought about by leaching were the hydration of minerals observed in the unleached waste to form ettringite and gypsum. The lime observed in the unleached waste was absent from the leached waste. The presence of anhydrite before and after leaching may indicate that not all of the hydration reactions went to completion. Quartz, hematite, and portlandite were all observed in both the leached and unleached waste. No field cells were constructed using Georgetown AFBC waste.

4.1.4 Comparison of the Crystalline Composition of Exxon, Alliance, and Georgetown FBC Waste

A summary of the crystalline composition of the three FBC wastes in the unleached and leached state is presented in Table 4-1. Both similarities and differences among the wastes can be seen. All three wastes contained

TABLE 4-1. PRINCIPAL CRYSTALLINE COMPONENTS IN LEACHED AND UNLEACHED FBC WASTES

Exxon PFBC			Alliance AFBC			Georgetown AFBC	
Unleached	Leached (Protocol)	Leached (Field Cell)	Unleached	Leached (Protocol)	Leached (Field Cell)	Unleached	Leached (Protocol)
quartz	quartz	quartz	quartz	quartz	quartz	quartz	quartz
anhydrite	gypsum	gypsum	anhydrite	gypsum	gypsum	anhydrite	anhydrite
periclase	brucite	brucite	calcite	calcite	calcite	calcite	gypsum
	calcite	calcite	lime	portlandite	portlandite	lime	calcite(?)
		ettringite	portlandite	hematite	hematite	portlandite	portlandite
			hematite	ettringite	ettringite	hematite	hematite
							ettringite

quartz, and anhydrite. The quartz undoubtedly originated as an impurity in the coal and were carried through the fluidized bed combustors generally unaffected. It also was left substantially unaffected by leaching. Anhydrite is one of the principal reaction products of the SO_2 in the combustors and the sorbent injected with the coal.

Some of the magnesium-bearing minerals observed in the Exxon PFBC waste were not seen in the AFBC waste (e.g., periclase). This difference is undoubtedly caused by the use of dolomite as the sorbent in the PFBC unit and the use of limestone as the AFBC sorbent. Likewise, portlandite, calcite, and lime, which occurred in both AFBC unleached wastes, were not present in the PFBC waste.

The effect of leaching was similar for all three wastes, subject to the mineralogical differences observed in the unleached waste. The presence of magnesium in the PFBC waste had some effect on the minerals observed in the leached waste; the brucite observed in the leached PFBC waste was not present in either of the AFBC wastes. The minerals that all three leached wastes had in common were gypsum and ettringite (except that the lab-leached PFBC waste lacked ettringite). Portlandite was observed in the two leached AFBC wastes but not in the leached PFBC waste (a similar pattern was observed for the unleached waste). Calcite was found in the leached Exxon PFBC and Alliance AFBC residue but not in the Georgetown AFBC waste. Anhydrite carried through the leaching of the Georgetown AFBC waste but not in the other two wastes.

4.1.5 FBC Waste From the EPA IERL-RTP Unit

During the development phase of the program, X-ray diffraction analysis was performed on waste from the FBC unit at EPA IERL, Research Triangle Park, North Carolina. During this time, AFBC-with-carbon-burnup cell (CBC) was still one of the technology front-runners, but there was concern for the availability of waste from a suitable source for the program. The objective of the early X-ray study of the IERL FBC waste was to determine the effect of the higher temperature of a carbon burnup cell on the composition and crystallinity of AFBC waste, so that the necessity of obtaining CBC waste could be evaluated. X-ray diffraction analyses were performed on bed draw material and waste from the primary cyclone before and after heating to CBC temperatures.

The results of the study showed that the higher temperatures (1055°C) of the carbon burnup cell compared to the FBC unit (840°C) had little effect on the bed draw material. The principal components both before and after heating were gypsum, lime, hematite, and calcium hydroxide.

The effects of heating were much more pronounced for the primary cyclone samples. Although gypsum and lime were observed before and after heating, the X-ray diffraction peaks observed for limestone, magnetite, quartz, hematite, and calcium hydroxide in the unheated sample were either completely absent after heating or were much lower in intensity, indicating a loss of crystallinity. The calcium carbonate observed before heating was apparently calcined to lime at the higher temperature.

4.2 Solids Composition of FBC Wastes

The chemical composition of samples of the three FBC wastes investigated were determined by sample digestion and chemical analysis of the digest solution. The procedures for the analysis and detailed results are summarized in Section 2.0 and given in detail in Appendix C.

As noted in Section 2.0, 26 parameters were included in the analysis of the whole-sample composition of the FBC wastes. The results of the analyses are reported in percent (g/100g) for the most abundant parameters (Al, Ca, Fe, K, Mg, Na, Si, SO_4, and Ti); the others are reported in concentration (mg/kg) in the solids analyzed.* This convention was adopted to avoid reporting small numbers with numerous zeros where concentrations are discussed in the text.

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*All percentages reported in this section are weight percent present in solids and not percent reduction or removal from the solids.

4.2.1 Composition of Exxon PFBC Waste

The solids composition of Exxon PFBC waste was determined for a variety of samples. The composite waste was analyzed both in the unleached and leached condition. In addition, individual components of the waste stream were analyzed. Also, the compositions of the feedstocks to the PFBC unit were determined.

4.2.1.1 Unleached and Leached Composite Waste

As noted, the composite PFBC waste was analyzed in the unleached and leached condition; the leached wastes studied were from the laboratory protocol (Step 1 and seven repetitions of Step 2) and from three field cells. The field cell samples were obtained by coring the cells at the conclusion of the field studies program (Appendix E). The core samples analyzed were representative samples taken from the full length of recovered core.

In the unleached condition, the Exxon PFBC waste was found to be composed of about 22% calcium, 22% sulfate, and 12% magnesium. Other major components were Si (5%), Fe (3%), Al (2%), and K (2%). Analysis of leached waste from the lab protocol showed that calcium, sulfate, and magnesium were decreased by the leaching, with reductions of 12%, 20%, and 8%, respectively. However, Al, Fe, K, Na, Si, and Ti were not significantly depleted. The concentrations of strontium, vanadium, and boron were reduced substantially. The concentration of Cr, Cu, Li, Mn, Mo, and Ni did not change significantly with leaching.

Chemical analysis of leached waste from the three field cells also showed substantial reduction in the content of calcium (to 14%), sulfate (to 18%) and magnesium (to 8%). Also depleted during the leaching were potassium, sodium, and silicon. Among the minor constituents, Cl, Co, Cu, Sr, and Zn were also reduced as a result of the leaching. The differences in the upper layer of disposal medium in the three cells cored had no effect on the composition of the leached waste, as evidenced by very close similarity in the compositions of the wastes from the three field cells.

4.2.1.2 Individual Waste Streams

The PFBC waste used for this program was composed of material from runs 79, 80, and 81 of the Exxon PFBC Miniplant. A bed draw composite and Cyclone No. 2 composite were prepared from runs 79 and 80. A Cyclone No. 3 composite was prepared from runs 80 and 81. Each of the three separate waste stream composites (bed draw, Cyclone No. 2, and Cyclone No. 3) were subjected to solids analysis.

The principal components of the bed draw were calcium (24%), sulfate (24%), and magnesium (14%). The Cyclone No. 2 composite was composed principally of sulfate (20%), silicon (13%), and calcium (12%). Magnesium, aluminum, and iron were also significant, with 8%, 6%, and 6%, respectively. Cyclone No. 3 produced waste consisting primarily of sulfate (22%), silicon (12-17%), and calcium (6-10%). Aluminum (7%), and iron (5%) were also important in the Cyclone No. 3 waste.

4.2.1.3 Coal and Dolomite Feedstocks

The feedstocks to the Exxon PFBC plant at the time the waste samples were obtained were Illinois No. 6 coal from the Monterrey mine and Pfizer 1337 dolomite from Ohio. The feedstocks were chemically analyzed for approximate contents of source materials for the waste. These analyses indicated that the feed coal is likely the primary source of Al, Fe, Na, Si, Be, Co, Mo, and Ni. The dolomite is probably the chief contributor of Ca, Mg, Ba, Cr, Cu, Sr, V, and Zn.

4.2.2 Composition of Alliance AFBC Waste

The Alliance AFBC waste was analyzed for several purposes, including determination of the effect of leaching, evaluation of sample representativeness, assessment of the effect of sample grinding, and determination of the effect of leaching with eluant previously equilibrated with disposal media.

4.2.2.1 Leached and Unleached Waste Samples

The Alliance waste was analyzed in the unleached state initially as a single sample and subsequently with multiple samples as a part of a sample representativeness test. The results of these tests were generally consistent; the predominant species found were Ca (31-35%), SO_4 (10-13%), Fe (5%), Si (3.6-4.2%), and Al (2%). Among the minor constituents, the highest concentrations were noted for B (generally 300-800 mg/kg), Cl (280 mg/kg), Sr (500-800 mg/kg), and Mn (550-820 mg/kg).

In the leached waste samples from the batch equilibration protocol, calcium was reduced to 20-21% and sulfate dropped to 1.4%. Iron and silicon were unaffected by leaching, with 5.3% and 4.2%, respectively. Chloride (420 mg/kg) and strontium (250 mg/kg) were also depleted substantially. Boron was reduced to 170-260 mg/kg, and manganese dropped to 250 mg/kg.

Leached wastes from the three field cells were very similar in composition. When the leached waste is compared to unleached waste, calcium was significantly reduced (21-24%) but sulfate was not (11%). Iron and silicon, the other two major components, were lower in the field cell wastes, with 3.0-3.5% and 1.2-1.8% respectively. B (240-280 mg/kg), Cl (270-360 mg/kg), Sr (240-320 mg/kg), and Mn (250-330 mg/kg) were apparently substantially leached from the waste during field cell operation.

4.2.2.2 Samples Leached With Disposal Medium Leachate

A special laboratory test was performed to evaluate how waste would leach when the eluant was a leachate that was previously equilibrated with samples of disposal medium. Two samples of Alliance AFBC waste were leached (one with shale and one with sandstone leachate) according to protocol Step 1 procedures.

The solids compositions of the waste samples thus leached were quite similar. As in the other leached Alliance wastes, the principal components were Ca (24%), SO_4 (4.7-7.5%), Fe (4.5-4.9%), and Si (3.2-3.4%).

Some depletion of calcium and sulfate was again observed; iron and silicon were not greatly affected. Among the minor constituents, boron remained high at 500-800 mg/kg, chloride dropped to 400-420 mg/kg, strontium decreased to 160-170 mg/kg, and manganese decreased to 520-530 mg/kg. The results of leaching with disposal medium leachate was thus quite comparable to the results obtained by "ordinary" leaching with deionized water. Slightly less calcium and sulfate were leached, and boron and manganese were decreased somewhat less also. Chloride remained at about the same level, and strontium was decreased to a lower concentration in the leached waste.

4.2.3 Composition of Georgetown AFBC Waste

In the unleached condition, the principal elemental components of the Georgetown waste were Ca (32%), SO_4 (8.5%), Al (3%), and Fe (3%). Among the minor components, the highest concentration were noted for B (390 mg/kg), Cl (320 mg/kg), F (290 mg/kg), Mn (290 mg/kg), and Sr (260 mg/kg).

The leached (protocol Steps 1 and 2) Georgetown AFBC waste was found to have a significantly reduced calcium content (15-23%). Silicon (4.3-5.3%), aluminum (2.4%), and iron (2%) appeared to be slightly depleted during leaching. Sulfate was found to be 7%. For the minor components, chloride was reduced to 100 mg/kg, and strontium decreased to about 50 mg/kg. Boron, fluoride, and manganese were largely unchanged by the leaching, with 290-470 mg/kg, 270-390 mg/kg, and 190-280 mg/kg, respectively.

4.2.4 Comparison of the Whole-Sample Analysis Results for the Three FBC Wastes

A summary of the solids analysis results for the three FBC wastes is shown in Table 4-2. The principal components of all three wastes were generally the same and included Ca, Si, Al, Fe, and SO_4 (except for the Georgetown waste, which had low SO_4). The calcium content of unleached Alliance and Georgetown AFBC waste was about the same and constituted about 1/3 of the bulk of the solid. For Exxon PFBC waste, the calcium content was

TABLE 4-2. PRINCIPAL ELEMENTAL COMPOSITION OF UNLEACHED AND LEACHED FBC WASTE[1]

Element/ Species	Exxon PFBC			Alliance AFBC			Georgetown AFBC	
	Unleached	Leached (Protocol)	Leached (Field Cell)	Unleached	Leached (Protocol)	Leached (Field Cell)	Unleached	Leached (Protocol)
Ca	22	11–12	14–15	31–35	21	21–24	32	15–23
SO_4	22	20	16–19	10–14	1.4	11	8.5	6.4–7.5
Mg	12	7.8–8.0	7.6–7.8	0.36–0.47	0.43–0.52	0.21–0.23	0.46	0.34–0.44
Si	5.1–5.2	6.5–6.7	2.3–5.3	3.6–4.2	4.2	1.2–1.8	5.8	4.3–5.3
Fe	3.0	4.0	3.0–3.6	5.1–5.3	5.3	3.0–3.5	2.8	1.9–2.4
Al	2.4	2.7	2.1–2.7	1.8–2.0	1.8–2.6	1.0–1.4	2.9	2.2–2.5
K	2.1–2.2	2.1–2.2	2.8–3.1	0.3–0.4	0.3–0.4	0.2–0.4	0.5	0.4
Na	0.2–0.8	0.4–0.9	0.2–0.3	0–0.14	0–0.06	0.11–0.14	0.14	0.07–0.09

[1] Units are weight percent.

lower (22%), but magnesium was high (11.6-11.9%), reflecting the dolomite sorbent feed. The Alliance waste had about half as much sulfate (10-13%) as the Exxon waste (23%); the Georgetown waste had 8.5% sulfate. The iron, silicon, and aluminum content of all three wastes were quite similar and ranged generally from 2 to 6%.

Laboratory leaching resulted in significantly reduced calcium content for all three wastes (about 50% for the Exxon waste and 30% for the Alliance and Georgetown wastes). Magnesium was reduced from about 11.7% to about 7.7% during lab leaching of the Exxon waste. Sulfate was reduced in the Exxon and Alliance waste (from 23% to 20% and from 12% to 1.4%, respectively. Silicon, iron, and aluminum were leached only slightly or not at all.

Field cell leaching of the Exxon PFBC waste resulted in a decline from 22% to 15% for calcium, 23% to 18% for sulfate, and 11.8% to 7.7% for magnesium. For the Alliance AFBC waste, field cell leaching led to a reduction from 33% to 23% for calcium, but sulfate did not appear to be depleted substantially compared to unleached waste.

4.3 Composition of FBC Waste as Determined by X-Ray Fluorescence and Electron Microprobe

The compositions of all three FBC wastes were determined in the unleached and leached condition by X-ray fluorescence (XRF). The leached samples examined were from Steps 1 and 2 of the laboratory protocol. The X-ray fluorescence analyses were interpreted in qualitative fashion. Electron microprobe analysis was performed on the unleached Exxon PFBC waste only. Details are given in Appendix C.

The XRF studies corroborated the results of the other whole-sample chemical analyses of the solids. For all three wastes, the elemental compositions were found to comprise principally Ca, S, Si, and Al. Magnesium was also found in the Exxon PFBC waste, and iron was observed in all waste specimens, but in relatively smaller amounts. The XRF spectra of 5 different Alliance AFBC waste samples were virtually identical, indicating that there was no significant difference in the compositions of the samples; all were found to be equally representative of the bulk waste.

Potassium was observed in all three wastes in small quantities but was almost completely removed during leaching, as it was not observed in the leached waste. Leaching did not generally cause the relative intensities of any of the peaks on the XRF spectra to change, indicating that the relative amounts of the various elements present did not change substantially. Leaching of the Alliance AFBC waste with leachate previously equilibrated with disposal media samples resulted in depletion of the potassium but otherwise did not cause any changes of the XRF spectra.

Electron microprobe analysis, which was performed only on the Exxon PFBC waste, allows the elemental compositions to be determined at different depths in individual waste particles. In this way, differences in the "surface" versus "bulk" composition of the particles can be assessed. The analysis of selected PFBC waste particles at two different depths found no significant difference in the proportions of elements at the two depths, except that iron was more abundant in the deeper than in the more shallow levels.

4.4 Ultimate and Proximate Analysis of FBC Wastes

As a part of the overall chemical characterization program, both proximate and ultimate analyses were performed on the Exxon PFBC waste and Alliance AFBC waste. Analysis of the three component waste streams from the Exxon PFBC unit showed that the Cyclone No. 3 material contained a small amount of incompletely combusted material (89 Btu/lb), whereas the other waste streams (bed draw and Cyclone No. 2) contained no combustible material. These analyses also showed that the highest sulfur content was in the bed draw material. Leaching (protocol Steps 1 and 2) of the Exxon PFBC waste was found to reduce the ash content by about 15% and the sulfur content by about 50%.

The ultimate and proximate analyses of the Alliance AFBC waste showed some remaining combustible material; an anomalously low 38 Btu/lb was found in the unleached waste and about 330 Btu/lb were present in the leached waste. The anomoly for the unleached waste may be due to sample variability. The ash content was reduced about 10% and the sulfur content about 40% as a result of the sample leaching.

4.5 Physical Properties of FBC Wastes

As noted in Section 3.0, several physical properties of the three FBC wastes were determined, including the particle size distribution, particle surface characteristics, specific gravity, and specific surface area. Appendix B presents the details of the procedures and results.

4.5.1 Particle Size Distribution

Samples of mixed (composite) samples of unground Exxon PFBC, Alliance AFBC, and Georgetown AFBC wastes were dry-sieved to determine the particle size distribution of the "as-received" wastes. The mean particle sizes of these wastes were found to be 195 microns for the Exxon waste, 270 microns for the Alliance waste, and 230 microns for the Georgetown waste. The particle size distributions were quite similar for the Exxon and Alliance waste, although the Exxon waste was consistently finer grained. The Georgetown waste had a different grain size distribution than the other two wastes in that there was a higher percentage of material in the range below 100 microns. The particle-size distribution curves for the three wastes are given in Appendix B.

A single particle-size analysis was performed on the Exxon PFBC waste after grinding to the same extent as during sample preparation for the batch equilibration protocol. This analysis was performed on a SediGraph Particle Size Analyzer, which required sample preparation in which the fraction coarser than 104 microns was removed. This fraction coarser than 104 microns constituted about 57% of the ground Exxon PFBC waste. Of the remaining 43%, the average particle size was 14.5 microns.

4.5.2 Particle Shape and Surface Characteristics

In order to assess particle shapes and particle surface characteristics, scanning electron micrographs were taken of all three FBC wastes both in the unleached and leached condition. Micrographs were obtained at a low and a high magnification (generally 300X and 3000X). The leached wastes were from Steps 1 and 2 of the laboratory batch equilibration protocol. The micrographs are contained in Appendix B.

Exxon PFBC Waste

The unleached Exxon PFBC waste was found to consist of irregularly shaped particles covered with fine material. A few spherical particles were also present. The leached waste also consisted mostly of irregular particles, but it contained in addition lath-shaped particles approximately 30 to 60 microns long and 7 to 10 microns across. These particles were probably precipitated from solution during leaching (possibly calcite) or may have been the hydration products of calcium sulfate, possibly gypsum.

Alliance AFBC Waste

The unleached Alliance AFBC waste was also found to consist mostly of irregular particles and a few spheres. Some of the particles appeared to have crevices in them resembling a defect-structure. Several samples obtained from the Alliance waste for an evaluation of sample representativeness were found to have a very similar appearance in all the electron photomicrographs. Leached waste consisted of generally smaller particles than the unleached waste and contained laths similar to those observed in the PFBC waste.

Samples of Alliance AFBC waste were also leached with leachate previously obtained by Step 1 and 2 leaching of shale and sandstone disposal media samples. Scanning electron micrographs of these samples showed an appearance of the sample quite similar to the samples that were leached with deionized water. There was also apparently significant deposition of small particles on the surfaces of the larger particles.

Georgetown AFBC Waste

Unleached Georgetown AFBC waste was found to contain two different groups of particle sizes. It is likely that the larger group was derived from the bed draw and the smaller groups was from the fly ash component of the waste. The finer particles appeared to adhere to the coarser grains. Leached waste was found to contain little of the original fine fraction. Instead, small needles were observed to adhere to the coarser grains.

4.5.3 Specific Gravity and Specific Surface Area

The specific gravities for the Exxon PFBC, Alliance AFBC, and Georgetown AFBC wastes were determined to be 2.49, 2.65, and 2.42, respectively. The apparent bulk densities after sample grinding were 1.10, 1.29, and 1.21 g/cc, respectively. The specific surface area was obtained for the ground Exxon PFBC waste and was found to be 0.9 m^2/g.

4.5.4 Field Permeability

The field permeability of Alliance AFBC and Georgetown AFBC waste was determined by constructing large (4-foot diameter and 4-foot long) cylindrical permeameters at the Crown field site. The waste was not compacted when put in the cells. The details of the construction and operation of the permeameters are given in Appendix E. The permeability of the waste was determined initially, at an interim point in the program, and at the conclusion of the field studies. The Alliance AFBC permeameter was operated about 19 months, and the Georgetown AFBC permeameter was in place for about 13 months. Data are given here for the initial permeability and for the value after comparable periods of operation.

The initial permeabilities of the two wastes were quite comparable, with 1.1×10^{-3} cm/sec for the Alliance AFBC waste and 1.7×10^{-3}

cm/sec for the Georgetown AFBC waste. These initial permeabilities are within the range expected for a fine sand. After 15.5 months of operation, the permeability of the Alliance AFBC waste decreased to 1.1 x 10^{-4} cm/sec, which is typical of a clayey silt. The permeability of the Georgetown waste decreased to 1.7 x 10^{-5} cm/sec after 13 months of operation. This permeability is comparable to a typical clay.

4.6 Summary of FBC Waste Composition

The findings of the different methods of analysis of the composition and physical properties of the FBC waste generally corroborate each other. The minerals in the unleached composite Exxon PFBC waste included anhydrite, periclase and quartz. The bulk solids chemical composition reflected the mineral composition, with 22% calcium, 12% magnesium, and 22-23% sulfate. After leaching in the lab protocol, the principal minerals were gypsum, brucite, calcite, and quartz. Field cell leaching produced a similar mineral suite, but with the addition of ettringite. The solids composition of both the lab- and field-leached PFBC waste showed a reduction in calcium, sulfate, and magnesium. Both the mineral and chemical composition data indicate the addition of water to the minerals during leaching. The mineral and chemical composition also reflect a higher magnesium content in the PFBC waste than in the AFBC wastes, which is a result of the use of dolomite rather than limestone as the sorbent. Electron photomicrographs of the unleached PFBC waste showed predominantly irregular particles, probably the quartz, anhydrite, and periclase. The lath-shaped particles in the leached wastes were probably gypsum or calcite crystals.

Unleached and leached Alliance AFBC waste had in common the minerals quartz, calcite, portlandite, and hematite. The waste differed in that the unleached waste had anhydrite and lime whereas the leached waste had gypsum and ettringite. Unleached Alliance waste had 31-35% calcium and 10-13% sulfate. Lab leaching resulted in a reduction of calcium to 20-21% and of sulfate to 1.4%. Field cell leaching lowered the calcium to 21-24%, but sulfate remained at 11%. Scanning electron micrographs indicated the addition of lath-shaped (presumably gypsum) particles to the irregular particles found in the unleached waste as leaching occurred.

The mineral composition of the Georgetown AFBC waste showed similar changes during leaching. The anhydrite observed in the unleached waste was partially converted to gypsum during leaching. Lime in the unleached waste was converted to other minerals, and ettringite was formed during the leaching process. Before leaching, the Alliance waste was composed of 38% calcium and 8.5% sulfate. Lab protocol leaching reduced the calcium to 15-23% and the sulfate to 6.5-7.5%.

5.0 LEACHING CHARACTERISTICS OF FBC WASTES

As noted in Section 3.0, the leaching characteristics of Exxon PFBC, Alliance AFBC, and Georgetown AFBC wastes were assessed by several methods in the laboratory and field. The most important laboratory leaching study was leaching according to the sequential batch equilibration protocol. The results of Steps 1, 2, and 3 of the protocol (the leaching steps) are described here; Steps 4, 5, and 6 (the attenuation steps) are presented in Section 6.0. The entire protocol is summarized in Section 3.0 and described in detail in Appendix D. Some of the steps of the protocol were performed for different lengths of time (one, two, and seven days) to evaluate the effect of time of leaching. All steps were performed for the seven-day period for all wastes, so the results from this time of leaching are reported here. A description of the effect of the time of leaching is given in Appendix D.

The leachates used to assess the leaching behavior of FBC wastes under field conditions were from the upper sample point of the field cells. These leachates reflected the chemical changes resulting from passage through a one-foot overlayer of disposal medium and an 18-inch thick layer of FBC waste. Details of the field cell studies are given in Appendix E.

A small study of the leaching characteristics of the FBC wastes in laboratory leaching columns was also performed. Exxon PFBC and Alliance AFBC wastes were used in five columns; three of the columns included an overlayer of disposal medium to simulate landfill cover material, and two columns had an additional disposal medium layer below the waste layer to simulate landfill substrate material. All leachate samples were collected at the base of the columns after passing through all the layers in the columns.

Leachates from the columns with only the waste and an overlayer of disposal medium were comparable to leachates from the upper sample point of the field cells. Leachates from the columns with both an overlayer and underlayer of disposal medium were comparable to leachates from the lower sample point of the field cells. The results from the columns with an overlayer and underlayer of disposal medium reflect the attenuation that occurs as the leachate flows through the lower disposal medium layer and could thus be included in Section 6.0 rather than in this section. However, the results are included here so that they can be more easily compared with the data from the three columns without the lower disposal medium layer.

The characteristics of leachates generated in the lab and field components of the study are discussed in succeeding paragraphs for each of the three wastes in turn. A summary comparison among the three wastes is then given.

5.1 Leaching Characteristics of Exxon PFBC Waste

As noted, the leaching characteristics of Exxon PFBC waste were assessed in the laboratory batch equilibration protocol, in the small laboratory leaching column experiment, and in the large-scale field cells. In addition, the RCRA Extraction Procedure was performed on the waste to ascertain if it would be classed as hazardous (in the toxicity category) under current EPA regulations.

5.1.1 Batch Equilibration Leaching of Exxon Waste

The results of Step 1 leaching and repetitions of Step 2 and Step 3 leaching are described below.

5.1.1.1 Initial Leaching: Protocol Step 1

Step 1 of the batch equilibration protocol involved initial leaching of the Exxon PFBC waste with deionized water as the eluant. The leaching characteristics of the waste were assessed by determining the concentration of the various species of interest in the leachate and the weight percent leached from the waste for each species.

Table 5-1 shows the summary statistics for the concentrations of several species in leachate generated during Step 1, seven-day leaching of the Exxon PFBC waste. Calcium and sulfate had the highest concentrations, with means of 1670 and 1200 mg/L, respectively. The pH was also high at about 12. Specific conductance and TDS were also high, which is a reflection of the high calcium and sulfate levels. Other species with relatively high concentrations were potassium (250 mg/L), sodium (17 mg/L), and boron (10.5 mg/L).

The scatter of data is higher for calcium (standard deviation of about 180 mg/L) than for sulfate, which had a standard deviation of 60 mg/L. The standard deviation for pH was only 0.4.

Table 5-2 shows for each element or species the percent of the original bulk solids content (as determined in the solids composition analysis) that was extracted in Step 1. Only the A and B replicates of Step 1 leachate analysis were used in the computation of percent leached. The species showing the highest proportion leached were Cl (as much as 26%), B (20%), Sr (as much as 13%), Ca (6-8%), Na (5.2-5.4%), and SO_4 (about 5.5%). Thus, the species having the highest leachate concentration (calcium and sulfate) were also substantially leached from the waste.

5.1.1.2 Sequential Leaching of Waste with Fresh Eluant: Protocol Step 2

The Exxon PFBC waste was leached repeatedly with fresh deionized water as the eluant in protocol Step 2 to assess its potential to continue to contribute contaminants as leaching continued. The initial Step 2 leaching was performed on leached waste from Step 1. The PFBC waste was repeatedly leached in this manner seven times, and the leachate from each iteration was analyzed. For each element or species, the concentration was plotted for each iteration as a function of cumulative leachate volume (the volume was normalized for comparison with other components of the study to yield a

TABLE 5-1. SUMMARY STATISTICS FOR EXXON PFBC STEP 1 LEACHATES (7-DAY) LEACHATE CONCENTRATIONS[1]

Element/ Species	Number of Observations	Number of Values at Detection Limit	Mean	Median	Minimum	Maximum	Standard Deviation
Al	12	0	0.80	0.80	0.29	1.45	0.34
As	8	8	0.04	0.04	0.04	0.04	0
B	12	0	10.5	11.3	4.9	15.4	4.3
Ba	12	0	0.20	0.18	0.12	0.30	0.06
Ca	8	0	1670	1660	1340	1900	180
Cd	12	12	0	0	0	0	0
Cl	8	0	4.5	2.6	2.0	9.3	2.9
Co	12	8	0.59	0.07	0.07	2.2	0.79
Cr	12	2	0.09	0.10	0	0.20	0.06
Cu	12	8	0.02	0	0	0.09	0.03
F	12	0	0.96	0.83	0.67	1.94	0.35
Fe	12	0	0.19	0.17	0.07	0.39	0.09
K	12	8	250	20	20	800	350
Mg	12	0	1.4	0.68	0.16	6.3	1.8
Mn	12	7	0	0	0	0.01	0.01
Mo	4	0	2.5	2.4	2.2	2.9	0.33
Na	12	1	17	17	2.5	34	9.3
Ni	12	7	0.08	0.01	0.01	0.26	0.10
Pb	8	8	0.03	0.03	0.03	0.03	0
pH[2]	12	0	12.0	11.9	11.5	12.6	0.4
Se	8	8	0.06	0.06	0.06	0.06	0
Si	12	0	1.7	0.78	0.39	2.8	0.87
SO_4	12	0	1200	1210	1080	1260	60
Sp. Cond.[3]	12	0	8130	9500	2100	9800	2820
Sr	12	0	2.8	2.8	1.1	4.2	1.0
TDS	8	0	3210	3310	2220	4220	890
Ti	12	8	0.05	0	0	0.16	0.07
TOC	3	0	1.3	1.3	1.1	1.4	0.15
V	12	8	0.09	0	0	0.33	0.13
Zn	11	0	0.13	0.11	0.01	0.30	0.10

[1] Concentrations are in mg/L unless otherwise noted.
[2] Units are standard pH units.
[3] Units are micromhos/cm.

TABLE 5-2. WEIGHT PERCENT OF SELECTED SPECIES LEACHED FROM THE EXXON PFBC WASTE IN STEP 1 OF THE LABORATORY PROTOCOL

Element/ Species	Replicate A	Replicate B
Al	0.02	0.02
B	21	20
Ba	1.3	1.8
Be	-	-
Ca	6.1	7.5
Cd	<11	<11
Cl	26.2	8.9
Co	-	-
Cr	1.6	0.4
Cu	<0.04	<0.04
F	4.6	4.1
Fe	0.006	0.005
K	<2	<2
Li	-	-
Mg	0.014	0.006
Mn	<0.008	<0.008
Mo	-	-
Na	5.4	5.2
Ni	<0.4	0.4
Si	0.02	0.01
SO_4	5.4	5.5
Sr	6.7	13.6
Ti	<0.001	<0.001
V	<0.07	<0.07
Zn	0.4	0.4

volume-per-mass ratio on the abscissa on the plots). These concentration trends were then examined for patterns and were classified into three categories of concentrations trend (increase, decrease, and constant) with increasing volume-per-mass ratio. The results of this exercise are summarized in Table 5-3.

TABLE 5-3. CONCENTRATION TRENDS OF SELECTED SPECIES UPON SUCCESSIVE LEACHING (PROTOCOL STEPS 1 AND 2) OF EXXON PFBC WASTE

Element/Species	Trend
Al	Increase
B	Decrease
Ba	Slight Decrease
Ca	Decrease
Cr	Decrease
F	Constant
Fe	Slight Decrease
Mg	Decrease
pH	Slight Decrease
Si	Increase
SO_4	Constant
Sp. Cond.	Decrease
Sr	Decrease
TDS	Slight Decrease
Zn	Decrease

The species having the highest leachate concentration, calcium and sulfate, showed a decreasing and constant trend, respectively. The leachate pH decreased slightly. Only silicon and aluminum appeared to increase with increasing volume-per-mass ratio; all other species remained constant or decreased either substantially or slightly. Boron was noted to follow a classic desorption pattern for the Exxon PFBC waste with substantial concentrations in the early extracts.

In addition to the observations made for leachate concentration trends with increasing leaching, the total percent leached as a result of the Step 2 repetitions was determined. Table 5-4 shows the percent leached data for several elements and species of interest. Nearly half of the sulfate and strontium appeared to be leached out during repeated leaching. Also

TABLE 5-4. CUMULATIVE WEIGHT PERCENT EXTRACTED (AFTER STEP 1 AND SEVEN REPETITIONS OF STEP 2) FROM EXXON PFBC WASTE FOR SEVERAL PARAMETERS

Element/Species	Percent Leached
Al	0.3
Ca	31
Cl	38
F	18
Mg	0.05
Na	24
Si	0.2
SO_4	46
Sr	48

strongly leached were chloride (38%), calcium (31%), and sodium (24%). Aluminum and silicon were largely unaffected by leaching.

Comparison of Table 5-4 with Table 5-2 shows that typically 20 to 25% of the total which was leached during Step 1 followed by Step 2 repetitions was actually leached during Step 1. This observation is valid for most of the more soluble species, including Ca, Cl, F, Mg, Na, and Sr. Only 3 to 5% of the aluminum and silicon which ultimately leached out in Step 2 repetitions was leached out during Step 1.

5.1.1.3 Sequential Exposure of Leachate to Fresh Waste: Protocol Step 3

In protocol Step 3, the initial leachate that was used was from Step 1. Instead of the same sample of FBC waste being continually leached by fresh eluant, the same leachate was retained and repeatedly exposed to fresh waste. Thus, the cumulative volume-per-mass ratio, which began at 10 with Step 1 leachate, decreased with each Step 3 repetition. The final cumulative volume-per-mass ratio for the Exxon PFBC waste after the two repetitions performed was 3.33.

Table 5-5 shows the concentration trends with repetition of Step 3. As would be expected when the same leachate is re-exposed to fresh waste, most

TABLE 5-5. CONCENTRATION TRENDS OF SELECTED SPECIES IN EXXON PFBC WASTE WITH REPETITIONS OF PROTOCOL STEP 3.

Element/Species	Trend
Al	Slight Decrease
B	Increase
Ba	Increase
Ca	Increase
Cl	Increase
Cr	Increase
F	Increase*
Fe	Slight Decrease
Mg	Constant
Na	Increase
pH	Increase
SO_4	Increase
Si	Decrease
Sp. Cond.	Increase
Sr	Increase
TDS	Increase
Zn	Possible Increase

*Data Scattered

of the trends showed increasing concentration. Only aluminum, iron, and silicon showed a decrease, and magnesium remained constant.

The total mass of each species originally present in the samples used for the two repetitions of Step 3 was compared to the mass of each species that was actually leached, and a weight percent leached was calculated for each species (Table 5-6). Chloride, boron, and strontium were leached the most, with about 27%, 13%, and 9% leached, respectively. Sodium (4.6%), calcium (2.5%), sulfate (2%), and fluoride (1.4%) were also leached significantly. Aluminum and silicon were leached very little.

5.1.2 Laboratory Column Leaching of Exxon Waste

Three 24-inch long, three-inch diameter "leaching" columns containing layers of Exxon PFBC waste and disposal media were used to evaluate the characteristics of leachate generated under laboratory column conditions. The effect of grinding the waste was also assessed by using ground waste in some of the columns and unground waste in the others. Two of the columns

TABLE 5-6. TOTAL WEIGHT PERCENT OF SPECIES IN EXXON PFBC WASTE THAT WAS LEACHED BY TWO REPETITIONS OF PROTOCOL STEP 3

Element/Species	Percent Leached
Al	0.005
B	13
Ba	1.1
Ca	2.5
Cl	27
Cr	0.8
F	1.4
Fe	0.02
Mg	0.001
Na	4.6
Si	0.003
SO_4	2.0
Sr	9.2
Zn	0.1

NOTE: Percentages are averages for two replicate leachate samples.

contained a layer of waste overlain by a layer of shale; one of these columns (LC-2) contained ground waste and the other (LC-3) contained unground waste. The third column (LC-5) contained both an upper and lower layer of shale with a layer of ground waste between. As noted, leachate was collected from the bottom of all three columns, so the chemical characteristics showed the combined effect of exposure to the layers of shale and PFBC waste. The columns were operated for 114 days, and eight samples were collected and analyzed. Details of the construction and operation of the columns are given in Appendix D.

Ranges of concentration for the various species in the leachates from the two columns are given in Table 5-7. This table shows that for the lab leaching columns without the lower shale layer, the predominant species released were again calcium and sulfate. The pH was also again very high (11-12). Potassium and chloride concentrations were also high in leachates from the two columns without the lower shale layer. TDS and specific conductance reflected the calcium and sulfate values and were also high.

The effect of waste sample grinding on leachate concentrations was evaluated by comparing the results from Column LC-2 (containing ground

TABLE 5-7. RANGE OF SPECIES CONCENTRATIONS IN LEACHATES FROM LABORATORY COLUMNS CONTAINING EXXON PFBC WASTE[1]

Element/ Species	Column LC-2 Ground Waste Below Shale Layer	Column LC-3 Unground Waste Below Shale Layer	Column LC-5 Ground Waste Between Shale Layers
Al	0-1.7	0-1.9	0-2.1
B	1.6-25	2.3-25	1-13
Ba	0.3-1.2	0.4-0.9	0.3-1.2
Ca	300-1000	300-880	220-1300
Cl	10-410	17-260	18-220
Cr	0-0.33	0-0.4	0-0.24
Cu	0-0.10	0-0.12	0-0.06
F	0.3-0.8	0.025-0.67	0.29-0.69
Fe	0-0.19	0-0.34	0-0.82
K	150-3500	48-2500	38-65
Li	0.2-4.2	0-3.3	0-0.07
Mg	0-0.7	0-79	3-130
Mn	-	0-0.44	0-1.1
Mo	0.11-2.8	0.1-2.4	0-0.31
pH[2]	11-12	11-12	7.4-9.0
SO_4	1400-3000	1300-2900	1400-3700
Sp.Cond.[3]	3400-9500	2700-8500	2400-4000
TDS	2500-6700	2200-6900	1700-5100

[1] Units are mg/L unless otherwise noted.
[2] Units are standard pH units
[3] Units are micromhos/cm

NOTE: The indicated zero values are actually values below the detection limit for the analytical procedure used.

waste) and Column LC-3 (containing unground waste). This comparison shows no appreciable increase in the leachate concentration of any species as a result of grinding; most species had a higher range of concentration for the unground waste than for the ground waste.

Comparison of the results from Column LC-5 with the other columns shows that the lower shale layer did very little in attenuating calcium and sulfate. The initial pH (9.0) was elevated, although lower than in the other two columns, but was near neutrality for most of the period of column operation. Thus, pH was substantially reduced by the lower shale layer. The lower layer of shale also apparently substantially reduced the concentrations of potassium, lithium, and possibly molybdenum. Chromium, iron, and magnesium were appreciably mobilized from the shale rather than being attenuated.

5.1.3 Field Cell Leaching of Exxon Waste

The leaching behavior of Exxon PFBC waste under field conditions was evaluated by collection and analysis of leachates from the upper sample point of the field cells. The field cells were constructed to simulate an FBC waste landfill as closely as possible, so an upper foot of disposal medium was placed over the 18-inch layer of waste. Thus, the leachate from the upper sample point showed the effects of leaching both a layer of waste and an overlying layer of disposal medium. Two of the six Exxon PFBC field cells had shale in the upper layer. The upper layers of the other four cells were till, limestone, alluvium, and sandstone. All field cells were sampled initially from 4 August 1979 to 26 December 1980; twenty-five samples were collected and analyzed during that period. The cells were reactivated on 18 June 1981 and operated until 6 November 1981. Five samples were collected during the second sampling period.

In general, many of the species from the upper sample points had high concentrations in the first few samples collected, but the concentrations fluctuated widely. After the first month of operation, the concentrations oscillated less and smoother trends were observed. Table 5-8 presents a

TABLE 5-8. EXXON PFBC FIELD CELL ELUTION (UPPER SAMPLING POINT) CONCENTRATION BEHAVIOR FOR THE FIRST 20-30 DAYS OF OPERATION

Element/ Species	Cell 1 Shale	Cell 2 Shale	Cell 3 Glacial Till	Cell 4 Limestone	Cell 5 Alluvium	Cell 6 Sandstone
Al	Y	N	N	N	N	N
B	Y	Y	Y	Y	M	Y
Ba	I	I	I	I	I	I
Ca	I	I	I	I	I	I
Cd	Y	N	Y	Y	N	N
Cl	Y	Y	Y	Y	Y	Y
Co	Y	Y	Y	N	N	N
Cr	Y	Y	Y	Y	Y	Y
Cu	Y	Y	Y	N	Y	N
F	M	M	M	M	M	M
Fe	N	N	N	N	N	N
K	Y[1]	Y[1]	Y[1]	Y[1]	Y[1]	Y[1]
Mg	Y	Y	Y	Y	N	N
Mn	I	I	I	I	I	I
Mo	Y	Y	Y	Y	Y	Y
Na	Y	Y	Y	Y	Y	Y
Ni	N	N	N	N	N	N
pH	N	N	N	N	Y[1]	Y[1]
Si	N	N	N	N	N	N
SO_4	Y	Y	Y	Y	Y	Y
Sp.Cond.	Y	Y	Y	Y	Y	Y
Sr	N	N	N	N	N	N
TDS	Y	Y	Y	Y	Y	Y
Ti	N	N	N	N	N	N
V	N	N	N	N	M	N
Zn	Y	NB	Y	M	I	N

Y = Yes, early concentrations high (early concentrations are a factor of 4 to 5 or greater than later concentrations).
N = No, early concentrations not higher.
M = Modest (factor of 2 to 3 higher).
I = Inverse, early concentration low then increase.
[1] = Post day 20 (since early data at or near detection limit not considered reliable).
[2] = Significant pH drop (since pH is log base, factor of 4 to 5 not considered).

qualitative description of the observed concentration trends of the various parameters during the first 20 to 30 days of field cell operation. The parameters which showed a consistent dramatic decrease in concentration for all field cells were B, Cl, Cr, K, Mo, Na, SO_4, specific conductance, and TDS. Fluoride concentrations showed a moderate decrease with time for all field cells. Al, Fe, Ni, Si, Sr, Ti, and V showed no substantial decrease. The parameters showing an increase rather than a decrease in concentration with time were barium, calcium, and manganese. Cd, Co, Cu, Mg, pH, and Zn did not show consistent behavior for all field cells.

In order to gain insight into the long-term potential for leachate generation, the concentration ranges of the various parameters during the final phases of field cell operation were examined and categorized as shown in Table 5-9. These ranges were for samples taken on 17 July, 17 August, and 17 September 1981 for all field cells. Clearly, the parameters with the greatest concentrations were SO_4, TDS, Ca, K, Cl, Na, K, and Si. Al, B, Cr, Mg and Sr were also present in substantial concentration. The Exxon field cells with the different disposal medium overlayers were quite consistent in the ranges of concentrations they produced for each of the parameters.

5.1.4 RCRA Extraction Procedure Leaching of Exxon Waste

The Extraction Procedure (EP) as set forth by current EPA regulations promulgated under the provision of RCRA was performed on the Exxon PFBC waste. The extractant was analyzed for the eight metals specified by the regulations (Ag, As, B, Cd, Cr, Hg, Pb, and Se). None of the concentrations of these elements in the extractant was higher than the limit stipulated by the regulations, so the Exxon PFBC waste tested should be considered non-hazardous (in the toxicity category) under RCRA.

The EP extractants were also analyzed for other elements and species by the same analytical methods that were used routinely for the laboratory protocol, and a comparison was made with the Step 1 leachates. The column of eluant used in the EP was twice the volume used in Step 1. About twice as many species were found to be higher in the Step 1 leachate as were found

TABLE 5-9. APPROXIMATE CONCENTRATION RANGES OF PARAMETERS IN LEACHATES FROM THE UPPER SAMPLE POINTS OF THE EXXON PFBC FIELD CELLS

Approximate Concentration Range (mg/L)	Cell 1 Shale	Cell 2 Shale	Cell 3 Glacial Till	Cell 4 Limestone	Cell 5 Alluvium	Cell 6 Sandstone
10^3 to 10^4	SO_4,TDS	SO_4,TDS	SO_4,TDS	SO_4,TDS	SO_4,TDS	SO_4,TDS
10^2 to 10^3	Ca,K	Ca	Ca,K	Ca,K	Ca,K	Ca,K
10 to 10^2	Cl,Si,Na	Mg,K,Si, Na	Cl,Si,Na	Cl,Si,Na	Cl,Si,Na	Mg,Si,Na
1 to 10	Al,B,Mg, Si,Sr	B,Cl,Mg	B,Cl,Mg, Sr	Al,B,Cl,Mg, Sr	B,Li,Mg,Sr	B,Cl,Mg,Sr
10^{-1} to 1	Al,B,Co,Cu Fe,Mo,Ni,Ti V,Zn	Cd,Cr,Co,Cu Fe,Li,Mo,Ni Ti,V,Zn	Cd,Cr,Co,Cu Fe,Mn,Mo,Ni, Ti,V,Zn	Cd,Co,Cu,Fe Mn,Mo,Ni,Ti, V,Zn	Cd,Co,Cu,Fe, Mn,Mo,Ni,Ti, V,Zn	Cd,Cr,Co,Fe, Mn,Mo,Ni,Ti V,Zn
10^{-3} to 10^{-2}	Cr,Cu,Mn	Cr,Cu,Li,Mn	Cr,Cu,Mn			Cu

NOTE: Parameters spanning more than an order of magnitude are generally shown in more than one category.

to be higher in the EP extractant. Appendix D contains the data from this analysis.

5.2 Leaching Characteristics of Alliance AFBC Waste

The Alliance AFBC wastes were subjected to the same tests as the Exxon PFBC wastes to determine their leaching behavior. All three leaching steps of the lab batch equilibration protocol were performed, and the Alliance wastes were included in two of the lab leaching columns. Five field cells containing Alliance wastes were included in the field program.

5.2.1 Batch Equilibration Leaching of Alliance Waste

Steps 1, 2, and 3 of the batch equilibration protocol were performed on the Alliance AFBC waste.

5.2.1.1 Initial Leaching: Protocol Step 1

A summary of the concentrations observed in Step 1 leachates of the Alliance waste is shown in Table 5-10. The highest concentrations were found for calcium (1340 mg/L mean) and sulfate (1110 mg/L). The TDS (3870 mg/L) and specific conductance reflected the high calcium and sulfate values. The pH was also very high at 12.4. Other species that were somewhat elevated in concentration were potassium (40 mg/L), chloride (51 mg/L), and sodium (13 mg/L). The data scatter was quite high for calcium, with a standard deviation of 410 mg/L. For sulfate, the scatter was much less, with a standard deviation of 60 mg/L.

For each element or species, Table 5-11 shows the weight percent leached from the initial solid samples during Step 1. The results are shown for two replicates, A and B. The species which were most leached were chloride (about 63%) and strontium (about 25%). Molybdenum was also substantially leached (about 13%). Calcium and sulfate, which had the highest leachate concentrations, were 4.5% and 8.5% removed by leaching.

TABLE 5-10. SUMMARY STATISTICS FOR ALLIANCE AFBC STEP 1 (7-DAY) LEACHATE CONCENTRATIONS[1]

Element/ Species	Number of Observations	Number of Values at Detection Limit	Mean	Median	Minimum	Maximum	Standard Deviation
Al	36	1	1.04	1.02	0.02	2.58	0.66
B	36	0	3.5	3.3	0.7	8.0	2.3
Ba	36	1	0.13	0.11	0	0.25	0.07
Be	28	0	0	0	0	0.01	0.003
Ca	32	0	1340	1200	900	2770	410
Cd	36	1	0.04	0.04	0	0.10	0.03
Cl	36	0	51	51	43	62	4.1
Co	36	0	0.08	0.07	0.01	0.18	0.05
Cr	36	0	0.12	0.12	0.04	0.26	0.066
Cu	36	0	0.14	0.13	0.02	0.37	0.10
F	36	0	0.25	0.25	0.10	0.44	0.08
Fe	36	0	0.08	0.08	0.01	0.18	0.04
K	36	0	40	40	30	50	5.8
Li	28	0	0.36	0.37	0.25	0.46	0.07
Mg	36	8	0.81	0.66	0.02	2.7	0.86
Mn	36	0	0.02	0.02	0.01	0.04	0.01
Mo	36	0	0.42	0.43	0.35	0.49	0.03
Na	36	0	13.2	13.4	10.3	17.1	1.6
Ni	36	0	0.11	0.10	0.04	0.22	0.05
pH[2]	36	0	12.4	12.4	12.3	12.6	0.09
Si	36	0	0.55	0.54	0.33	0.96	0.16
SO_4	36	0	1110	1100	1010	1190	60
Sp. Cond.[3]	36	0	8100	8200	3250	8700	860
Sr	32	0	20.5	19.5	13.6	41.4	6.0
TDS	36	0	3780	3830	3500	4030	140
Ti	36	0	0.32	0.30	0.07	0.83	0.22
TOC	2	0	1.2	1.2	0.5	1.9	1.0
V	36	0	0.26	0.24	0.06	0.62	0.16
Zn	36	0	0.04	0.04	0.01	0.07	0.02

[1] Concentrations are in mg/L unless otherwise noted.
[2] Units are standard pH units.
[3] Units are in micromhos/cm.

TABLE 5-11. WEIGHT PERCENT OF SELECTED SPECIES LEACHED FROM THE ALLIANCE AFBC WASTE IN STEP 1 OF THE LABORATORY PROTOCOL

Element/ Species	Replicate A	Replicate B
Al	0.02	0.03
B	3.2	5.0
Ba	0.85	0.82
Be	0.21	0.42
Ca	4.4	4.71
Cd	55	90
Cl	62	64
Co	2.0	3.3
Cr	1.4	1.9
Cu	0.6	1.2
F	2.0	2.2
Fe	0.0004	0.0006
K	7.6	7.7
Li	-	-
Mg	0.07	0.16
Mn	0.012	0.015
Mo	12.3	14.8
Na	-	-
Ni	1.11	1.5
Si	0.008	0.009
SO_4	8.4	8.5
Sr	24	27
Ti	0.45	0.08
V	3.6	7.0
Zn	0.22	0.31

5.2.1.2 Sequential Leaching of Waste With Fresh Eluant: Protocol Step 2

The Alliance AFBC leached waste from protocol Step 1 was subjected to nine repetitions of Step 2 leaching to determine how the waste would continue to contribute contaminants with continued leaching. The concentrations were plotted as a function of cumulative volume of eluant per mass of waste, and the patterns observed were classified as increasing, constant, or decreasing. The results of this exercise are shown in Table 5-12.

With continued leaching, concentrations of the major species, calcium and sulfate, generally decreased, although sulfate decreased only slightly. The pH remained constant. The specific conductance remained constant, and the TDS decreased slightly. Of the remaining species, 14 increased in concentration with continued leaching and only seven decreased. It is apparent that for most species, the nine leachings at a 10:1 liquid-to-solid ratio were not sufficient to deplete the species significantly from the waste.

The removal of each species from the Alliance AFBC waste was further evaluated by computing the percent leached from the original bulk solids composition after seven of the nine repetitions of Step 2 (Table 5-13). The percent leached after seven (rather than nine) repetitions was used so that a comparison could be made with the Exxon waste, which was subjected to just seven repetitions. Chloride was the most strongly leached, with 86% removal. Strontium was also substantially removed (58% leached). Calcium and sulfate, which had the highest leachate concentrations, were 39% and 71% leached respectively. Aluminum and silicon were not greatly removed by leaching. Most of the species (except chloride) that were substantially leached showed decreasing concentration trends (Table 5-12).

Comparison of Table 5-12 with Table 5-10 allows an estimate to be made of the amount of the total quantity leached after Step 1 and seven repetitions of Step 2 that was actually removed during the initial Step 1 leaching. The initial Step 1 removal was highest for chloride (75%) and strontium (50%). The remaining parameters were removed 10-20% during Step 1 initial leaching.

TABLE 5-12. CONCENTRATION TRENDS OF SELECTED SPECIES UPON SUCCESSIVE LEACHING (PROTOCOL STEPS 1 AND 2) OF ALLIANCE AFBC WASTE

Element/Species	Trend
Al	Increase
B	Increase
Ba	Slight Decrease
Be	Increase
Ca	Decrease
Cd	Increase
Cl	Constant
Co	Increase
Cr	Increase
Cu	Increase
F	Decrease
Fe	Increase
K	Decrease
Li	Slight Decrease
Mg	Decrease then Increase
Mn	Increase
Mo	Decrease
Na	Decrease
Ni	Increase
pH	Constant
Si	Increase
SO_4	Slight Decrease
Sp.Cond.	Constant
Sr	Decrease
TDS	Slight Decrease
Ti	Increase
V	Increase
Zn	Increase

TABLE 5-13. CUMULATIVE WEIGHT PERCENT LEACHED (AFTER SEVEN REPETITIONS OF STEP 2) FROM ALLIANCE AFBC WASTE FOR SEVERAL PARAMETERS

Element/Species	Percent Leached
Al	0.4
Ca	39
Cl	86
F	10
Mg	1.0
Na	8.1
Si	0.09
SO_4	71
Sr	58

5.2.1.3 Sequential Exposure of Leachate to Fresh Waste: Protocol Step 3

Table 5-14 shows the concentration trends resulting from Step 3 leaching of the Alliance AFBC waste. Six replications of Step 3 were performed on the Alliance waste, resulting in a final cumulative volume-per-mass ratio of 1.43. Almost all of the parameters showed increasing concentrations with repetitions of Step 3; aluminum, beryllium, and silicon showed a decrease followed by an increase. Magnesium and pH were constant.

Table 5-15 shows the percentage of the mass of each species present in the Alliance AFBC solids that was leached during six repetitions of Step 3. The mass used in these calculations was the total mass available from all solids used in all repetitions of Step 3. Chloride and cadmium were leached the most, with 55% and 47% leached, respectively. K, Sr, Mo, V, and B were also substantially leached. Al, Fe, Mn, and Si were leached very little.

5.2.2 Laboratory Column Leaching of Alliance Waste

The range of concentrations for the various species leached from the Alliance AFBC waste in the lab leaching columns is shown in Table 5-16. Column LC-1 had a layer of ground waste overlain by a layer of sandstone; Column LC-4 had an additional layer of sandstone below the ground waste layer. Comparison of the results from Column Lc-4 with Column LC-1 enabled an evaluation of the attenuation effects of the lower sandstone layer to be made. Calcium and sulfate were clearly the predominant species leached in

TABLE 5-14. CONCENTRATION TRENDS OF SELECTED SPECIES IN ALLIANCE AFBC WASTE WITH REPETITIONS OF PROTOCOL STEP 3.

Element/Species	Trend
Al	Decrease then Increase
B	Increase
Ba	Increase
Be	Decrease then Increase
Ca	Increase
Cd	Increase
Cl	Increase
Co	Increase
Cr	Increase
Cu	Increase
Fe	Increase
Li	Increase
Mg	Constant
Mn	Increase
Mo	Increase
Na	Increase
Ni	Increase
pH	Constant
SO_4	Slight Increase
Si	Decrease then Increase
Sp.Cond.	Increase
Sr	Increase
TDS	Increase
Ti	Increase
V	Increase
Zn	Increase

TABLE 5-15. TOTAL WEIGHT PERCENT OF SPECIES CONTENT IN SOLIDS THAT WAS LEACHED BY SIX REPETITIONS OF PROTOCOL STEP 3 ON ALLIANCE AFBC WASTE

Element/Species	Percent Leached
Al	0.009
B	2.57
Ba	0.7
Cd	47
Cl	55
Co	1.6
Cr	1.2
Cu	0.6
F	0.2
Fe	0.0002
L	9.9
Mg	0.04
Mn	0.006
Mo	3.6
Ni	0.5
Si	0.002
SO_4	1.3
Sr	5.9
Ti	0.04
V	2.7
Zn	0.1

TABLE 5-16. RANGE OF SPECIES CONCENTRATIONS IN LEACHATES FROM LABORATORY COLUMNS CONTAINING ALLIANCE AFBC WASTE

	Column LC-1	Column LC-4
Element/ Species	Ground Waste Below Sandstone Layer	Ground Waste Between Sandstone Layers
Al[1]	0-1.4	0-3.7
B	0-2.1	1-5.8
Ba	0.4-1.2	0.3-0.9
Ca	730-1300	150-1300
Cl	4-1200	14-1300
Cr	0-0.33	0-0.22
Cu	0-0.073	0-0.125
F	0.21-0.52	0.3-0.40
Fe	0-0.17	0-0.67
K	79-950	68-210
Li	0.25-2.1	0-0.41
Mg	0-0.34	0-350
Mn	---	0-1.9
Mo	0.29-0.92	0-0.11
pH[2]	12	7.0-7.8
Sp.Cond.[3]	5800-7900	1500-5500
SO_4	960-2000	610-2800
TDS	2800-7000	840-6800

[1] Units are mg/L unless otherwise noted.
[2] Units are standard pH units
[3] Units are micromhos/cm

NOTE: The indicated zero values are actually values below the detection limit for the analytical procedure used.

both columns. Chloride and potassium were also present in high concentrations in the leachate. The pH was much higher in the column without the underlying layer of sandstone than in the column with the lower layer. Magnesium reached high levels in the column with the lower sandstone layer but not in the other column.

5.2.3 Field Cell Leaching of Alliance Waste

Five field cells containing Alliance AFBC waste were constructed and operated. Two of the cells contained alluvium in the disposal medium layers above the waste layer. The other cells had interburden, limestone, and shale in the overlayer. All cells were operated from 21 March 1980 to 19 October 1981; two of the cells were operated until 6 November 1981. During the period of operation, twenty-four samples were collected from the upper sample point and analyzed.

Table 5-17 provides a qualitative description of the concentration trends of the Alliance field cells during the initial period of operation. The species which decreased dramatically for all field cells during this initial period were Al, Cr, Cu, and pH. Chloride, titanium, and vanadium also decreased in the field cells for which concentrations were above the detection limit. Species whose concentrations did not change substantially during the early phase of operation were B, F, Fe, K, Li, Mg, Mo and Ni. Sulfate and strontium showed a modest increase or no change. An increase rather than a decrease was noted for calcium and manganese. Trends were different in leachates from different field cells for barium, sodium, and silicon.

The concentration ranges observed in leachates collected during the latter phases of field cell operation (17 July, 17 August, and 17 September 1981) are shown in Table 5-18. The parameters with the highest concentrations for all field cells were SO_4, TDS, Ca, and K. Also present in substantial concentrations were Cl, Si, Na, and Sr. The cells containing alluvium, particularly Cell 15, had more species in the lower concentration

TABLE 5-17. ALLIANCE AFBC FIELD CELL ELUTION (UPPER SAMPLING POINT) CONCENTRATION BEHAVIOR FOR THE FIRST 20-30 DAYS OF OPERATION

Element/ Species	Cell 13 Interburden	Cell 14 Alluvium	Cell 15 Alluvium	Cell 16 Limestone	Cell 17 Shale
Al	M	Y	Y	Y	Y
Ba	Y	M	N	N	N
B	N	N	N	N	N
Cd	DL	DL	DL	DL	DL
Ca	I	I	I	I	I
Cl	M	Y	Y	M	Y
Cr[1]	Y	Y	Y	Y	Y
Co	DL	DL	DL	DL	DL
Cu	Y	Y	Y	Y	Y
F	N	N	N	N	N
Fe	N	N	M	N	N
K	N	N	N	N	N
Li	N	N	N	N	N
Mg	N	N	N	N	N
Mn	I	I	N	I	I
Mo	N	N	N	N	N
Na	N	M	M	N	N
Ni	N	N	N	N	N
pH	Y	N	Y	Y	Y
Si	N	N	I	I	I
SO_4	N	M	N	N	N
Sp.Cond.	M	M	M	M	M
Sr	N	N	M	M	N
TDS	M	M	M	M	M
Ti	Y	Y	DL	DL	Y
V	Y	Y	Y	DL	M
Zn	DL	M	DL	DL	DL

Y = Yes, early concentrations high (early concentrations are a factor of 4 to 5 or greater than later concentrations).
N = No, early concentrations not higher.
M = Modest (factor of 2 to 3 higher).
I = Inverse, early concentration low then increase.
DL = At or near detection limit.
[1] = Declines seen at ≥60 days for Cr.

TABLE 5-18. APPROXIMATE CONCENTRATION RANGES OF PARAMETERS IN LEACHATES FROM THE UPPER SAMPLE POINTS OF THE ALLIANCE AFBC FIELD CELLS

Approximate Concentration Range (mg/L)	Cell 13	Cell 14	Cell 15	Cell 16	Cell 17
	Interburden	Alluvium	Alluvium	Limestone	Shale
10^3 to 10^4	SO_4,TDS	TDS	K,SO_4,TDS	SO_4, TDS	SO_4,TDS
10^2 to 10^3	Ca,K,SO_4	Cl,K,SO_4	Cl	Ca,K	Ca,K
10 to 10^2	Cl,Si,Na,Sr	Ca,Si,Sr	Ca,Si	Cl,Si,Na,Sr	Cl,Na,Sr
1 to 10	B,Mg	Li,Mg,Mo	Li,Mg,Mo,Sr	B,Li	B,Si
10^{-1} to 1	Al,Ba,B,Cr, F,Li,Mn,Mo	Al,B,Ba,Cr, F	Al,B,Ba	Al,B,Ba,Cr, F,Mg,Mn, Mo,Ti	Al,B,Ba,Cr, F,Li,Mg,Mo, Ti,V
10^{-2} to 10^{-1}	Cd,Cr,Co,Fe, Ni,Ti,V,Zn	Cd,Co,Ni,Ti, V,Zn	Cd,Cr,Co,F, Fe,Ni,Ti,V, Zn	Cd,Cr,Co,Cu, Fe,Ni,Ti,V, Zn	Cd,Cr,Co,Cu, Fe,Mn,Ni,Ti, V,Zn
10^{-3} to 10^{-2}	Cu	Cu,Mn	Cu,Mn	Cu	Cu

NOTE: Parameters spanning more than an order of magnitude are generally shown in more than one category.

range categories than the other cells, indicating that alluvium may be contributing less than the other media.

5.2.4 RCRA Extraction Procedure Leaching of Alliance Waste

The RCRA Extraction Procedure was performed on the Alliance AFBC waste, and the extracts were analyzed for the eight metals specified by the RCRA regulations. The results of these analyses showed the waste to be nonhazardous under the RCRA toxicity category.

5.2.5 Alliance Waste Leaching with Disposal Media Leachate

The Alliance AFBC waste was subjected to Step 1 and Step 2 leaching by leachate previously derived from Step 1 leaching of the shale and sandstone disposal media. Step 2 was carried through seven repetitions for this "media/waste" leachate. The leachate thus derived was compared with leachate derived from "normal" Step 1 leaching of the Georgetown waste with deionized water (Table 5-19). In general, higher concentrations were noted for the media/waste leachate than for the normal leachate only for B, Ba, Si, and TDS. Specific conductance was also somewhat higher. Lower concentrations were noted for Al, Be, Cr, Cu, Fe, Li, SO_4, and TIC. The remaining parameters were approximately the same for the leachates derived from the Alliance waste by deionized water, shale leachate, and sandstone leachate; some of these parameters were at or below the detection limit for all three leachates.

5.3 Leaching Characteristics of Georgetown AFBC Waste

The analyses performed to assess the leaching characteristics of the Georgetown AFBC waste were more limited than for the other two wastes. Only Steps 1 and 2 of the batch equilibration protocol were performed. No laboratory leaching columns were constructed with the Georgetown waste, and no field cells with Georgetown waste were operated. The RCRA Extraction Procedure, however, was performed on the waste.

TABLE 5-19. COMPARISON OF STEP 1 LEACHATE CONCENTRATIONS FOR ALLIANCE AFBC WASTE WHEN LEACHED BY DEIONIZED WATER AND WHEN LEACHED BY LEACHATE DERIVED FROM STEP 1 LEACHING OF SHALE AND SANDSTONE[1]

Element/ Species	Deionized Water	Shale Leachate	Sandstone Leachate
Al	0.89	0.32	<0.3
B	0.3	1.1	0.7
Ba	0.42	0.86	0.72
Be	0.006	<0.002	<0.002
Ca	1600	1600	1550
Cd	<0.04	<0.04	<0.04
Cl	53	57	56
Co	<0.03	<0.03	<0.03
Cr	0.032	<0.005	0.005
Cu	0.019	<0.005	<0.005
F	0.20	0.30	0.26
Fe	0.07	<0.04	<0.04
K	57	57	63
Li	0.45	0.34	0.37
Mg	0.65	0.19	0.19
Mn	<0.005	<0.006	<0.006
Mo	0.34	0.36	0.36
Na	19	18	18
Ni	<0.02	<0.02	<0.02
pH[2]	12.3	12.4	12.4
Si	<0.2	1.1	1.7
SO_4	1400	1320	1435
Sp.Cond.[3]	7400	8950	8950
Sr	22	21	21.5
TDS	3900	4500	4525
TIC	3	2	<0.03
TOC	4.7	3.8	<2.0
Ti	<0.03	<0.03	1.7
V	0.12	<0.02	<0.02
Zn	<0.02	<0.02	<0.02

---

[1] Concentrations are in mg/L unless otherwise noted.

[2] Units are standard pH units

[3] Units are micromhos/cm

5.3.1 Batch Equilibration Leaching of Georgetown Waste

As noted, Step 1 and 2 of laboratory protocol were performed on the Georgetown waste.

5.3.1.1 Initial Leaching: Protocol Step 1

The summary statistics for Step 1 leaching of the Georgetown AFBC waste are shown in Table 5-20. The species with the highest concentrations were calcium and sulfate, with mean values of 1500 and 1400 mg/L, respectively. The data scatter was relatively small, with standard deviations of 90 and 120 mg/L, respectively, for calcium and sulfate. Other species with lower but still substantial concentrations were chloride (24 mg/L), potassium (18 mg/L), and strontium (13 mg/L). The mean pH value was 12.5. The TDS and specific conductance reflected the high concentrations of calcium and sulfate.

Table 5-21 shows for each species the percent available in the waste that was leached during Step 1. Results are shown for two replicates, A and B. Chloride and strontium were the species that leached the most, with about 63% and 52% removal, respectively. Also substantially leached were sulfate (17%) and lithium (12.5%). Calcium was 5% removed.

5.3.1.2 Sequential Leaching of Waste with Fresh Eluant: Protocol Step 2

The concentration trends observed upon successive leaching of the same waste sample with fresh eluant during repetition of Step 2 on the Georgetown AFBC waste are shown in Table 5-22. Most species displayed decreasing concentration in individual aliquots as leaching progressed, including Ca, Cl, Cr, Li, Na, pH (slight), Si, SO_4, specific conductance, Sr, TDS, and TIC. No species showed an increase in concentration with increased leaching, although barium showed an initial increase followed by a decrease. Fluoride and TOC were constant.

TABLE 5-20. SUMMARY STATISTICS FOR GEORGETOWN AFBC STEP 1 (SEVEN-DAY) LEACHATE CONCENTRATIONS[1]

Element/ Species	Number of Observations	Number of Values at Detection Limit	Mean	Median	Minimum	Maximum	Standard Deviation
Al	6	5	0.17	0.13	0.13	0.42	0.12
B	6	3	0.16	0.05	0.02	0.44	0.20
Ba	6	0	0.19	0.19	0.19	0.20	0.01
Be	6	4	0	0	0	0	0
Ca	6	0	1500	1500	1400	1600	90
Cd	6	6	<0.02	<0.02	<0.02	<0.02	0
Cl	6	0	23.7	23.5	23	25	0.8
Co	6	6	<0.01	<0.01	<0.01	<0.01	0
Cr	6	2	0.05	0.05	0	0.10	0.05
Cu	6	4	0.03	0	0	0.08	0.04
F	6	0	0.16	0.15	0.11	0.25	0.05
Fe	6	6	<0.02	<0.02	<0.02	<0.02	0
K	6	0	18	18	16	20	1.6
Li	6	0	0.5	0.49	0.40	0.61	0.09
Mg	6	0	2.7	2.8	1.7	3.2	0.6
Mn	6	2	0.01	0.01	0	0.02	0.01
Mo	6	4	0.02	0	0	0.06	0.03
Na	6	0	6.5	6.5	4.9	8.2	1.1
Ni	6	2	0.04	0.05	0.01	0.07	0.03
pH[2]	6	0	12.5	12.5	12.5	12.6	0.04
Si	6	0	2.4	2.5	1.1	4.0	1.1
SO_4	6	0	1400	1390	1210	1530	120
Sp. Cond.[3]	6	0	7800	7700	7500	8300	310
Sr	6	0	13.2	13	13	14	0.4
TDS	6	0	4000	4050	3740	4100	140
Ti	6	4	0.06	0.01	0.01	0.18	0.08
TIC	6	2	4.3	5.7	1.0	6.3	2.6
TOC	6	0	3.9	3.6	3.5	4.6	0.5
V	6	4	0.02	0.01	0.01	0.03	0.01
Zn	6	6	<0.01	<0.01	<0.01	<0.01	0

[1] Concentrations are in mg/L unless otherwise noted.
[2] Units are standard pH units.
[3] Units are in micromhos/cm.

TABLE 5-21. WEIGHT PERCENT OF SELECTED SPECIES LEACHED FROM THE GEORGETOWN AFBC WASTE IN STEP 1 OF THE LABORATORY PROTOCOL

Element/ Species	Replicate A	Replicate B
Al	<0.01	<0.01
B	<0.1	0.21
Ba	1.3	1.2
Be	–	–
Ca	5.0	5.0
Cd	–	–
Cl	62	65
Co	<3	<3
Cr	0.36	0.92
Cu	<0.2	<0.2
F	0.38	0.52
Fe	<0.001	<0.001
K	3.6	3.6
Li	12.3	12.8
Mg	0.67	0.63
Mn	0.021	0.055
Mo	<1.4	<1.4
Na	4.1	3.5
Ni	<0.9	3.9
Si	0.041	0.045
SO_4	16.4	18.1
Sr	54	50
Ti	<0.01	0.01
V	<0.3	<0.3
Zn	<0.4	<0.4

TABLE 5-22. CONCENTRATION TRENDS OF SELECTED SPECIES UPON SUCCESSIVE LEACHING (PROTOCOL STEPS 1 AND 2) OF GEORGETOWN AFBC WASTE

Element/Species	Trend
Ba	Increase then Decrease
Ca	Decrease
Cl	Decrease
Cr	Decrease
F	Constant
K	Constant
Li	Decrease
Na	Decrease
pH	Slight Decrease
Si	Decrease
SO_4	Decrease
Sp. Cond.	Decrease
Sr	Decrease
TDS	Decrease
TIC	Decrease
TOC	Constant

Table 5-23 shows the percent leached during repetitions of Step 2 for several species of interest. About 75% of the soluble species, chloride, was leached. Calcium (26%) and sodium (17%) were also substantially removed by leaching. Sulfate was also apparently leached considerably; strontium was strongly (perhaps completely) leached, although the results cannot be quantitated because the leaching data showed somewhat greater removal than was present in the unleached waste.

TABLE 5-23. CUMULATIVE WEIGHT PERCENT LEACHED (AFTER NINE REPETITIONS OF STEP 2) FROM GEORGETOWN AFBC WASTE FOR SELECTED PARAMETERS

Element/Species	Percent Leached
Ca	26
Cl	75
F	2.3
Mg	1.4
Na	17
Si	0.2
SO_4	<46
Sr	>100

Comparison of Table 5-23 with Table 5-21 shows that about 85% of the total chloride leached was removed by Step 1 leaching before Step 2 leaching commenced. Of the total magnesium leached during Steps 1 and 2, 46% was leahced in Step 1. The percent of total leached that was removed during Step 1 was about 20% for Ca, F, Na, and Si.

5.3.2 RCRA Extraction Procedure Leaching of Georgetown Waste

Extraction and analysis of the Georgetown waste by RCRA procedures showed that the waste is nonhazardous in the toxicity category.

5.4 Comparison of Leaching Characteristics of FBC Wastes

The leaching results for the three FBC wastes as described in this section have been plotted on a single diagram for each parameter in Appendix I, and a detailed comparative analysis is given for each parameter. The summary comparison given in the following paragraphs is taken from this section and from Appendix I. It is recognized that the laboratory and field results are not directly comparable because of the large differences in the ratios of the volume of eluant to the mass of waste leached. However, the results are discussed together to show where differences and similarities in the leaching systems occur.

For the Exxon PFBC waste, the leachates from the laboratory protocol, the lab leach columns, and the field cells are highest in calcium and sulfate. Calcium had a mean Step 1 concentration of 1670 mg/L, ranged generally from 300 to 1000 mg/L in the lab leaching columns (without the disposal medium underlayer) and was generally in the 200 to 700 mg/L range in the field cell leachates (last three samples). For sulfate, the mean Step 1 concentration was about 1200 mg/L, and the lab leaching column leachates were in the 1300 to 3000 mg/L range. The field cell leachates were in the 1000 to 2500 mg/L range for sulfate. The pH was very high in PFBC waste leachates from the protocol and the lab leaching columns, but was generally only one unit above neutrality in the field cell leachates. As expected, the TDS and specific conductance was high, reflecting the high calcium and sulfate concentrations.

Calcium and sulfate were the predominant species in leachates from the Alliance AFBC waste, also. The mean protocol Step 1 calcium concentration was 1340 mg/L, and the lab leaching columns had a general concentration range of 730 to 1300 mg/L. The field cells varied somewhat in the concentration of calcium (during the last months of operation) for the different cells; the cells containing interburden, limestone, and shale had a range of 300 to 500 mg/L, whereas the alluvium-leaching cells had concentrations less than 100 mg/L. Sulfate levels in Alliance leachates were quite high, with a mean Step 1 value of 1110 mg/L and a range of 960 to 2000 in the lab leaching columns. Field cell leachates were in the 900 to 1500 mg/L range. The pH of leachates from the lab studies was very high (generally greater than 12), but was only one unit above neutral in the field cell leachates.

For the Georgetown waste, the most important parameters were again calcium and sulfate. The mean Step 1 leachate concentration was 1500 mg/L for calcium and 1400 mg/L for sulfate. The mean pH value for the Step 1 leachate was about 12.5.

It is clear that calcium and sulfate are leached from all three FBC wastes in comparable concentrations. The pH, which is very high in the laboratory leachates, appears to be of much less potential concern under field conditions. During Step 2 repeated leaching, calcium was about 31% leached from the Exxon waste, 39% leached from the Alliance waste, and about 26% leached from the Georgetown waste. About 50%, 71%, and >40% of the sulfate was leached, respectively, for the Exxon, Alliance, and Georgetown waste.

Other parameters with relatively high concentrations in the Step 1 leachates were potassium (251 mg/L), sodium (17 mg/L), and boron (10.5 mg/L) for the Exxon waste. For the Alliance waste, the more significant parameters were chloride (51 mg/L), potassium (44 mg/L), and sodium (13 mg/L).

The significant species for the Georgetown waste were chloride (24 mg/L), potassium (18 mg/L), and strontium (13 mg/L).

For the lab leach columns, Exxon PFBC waste had elevated concentrations of potassium (40-1000 mg/L) and chloride (10-50 mg/L) in the leachates. The Alliance lab leach column also contained elevated potassium (70-1000 mg/L) and chloride (40-500 mg/L) concentrations.

The Exxon PFBC field cells had relatively high concentrations of potassium (50-800 mg/L), chloride (4-100 mg/L), sodium (20-300 mg/L), and silicon (6-50 mg/L) during the latter months of operation. The Alliance cells also had higher concentrations of potassium (100-1000 mg/L), chloride (20-300 mg/L), sodium (10-200 mg/L), and silicon (5-60 mg/L).

Clearly the Exxon and Alliance are also very similar in the parameters and associated concentration with respect to species of secondary interest. Potassium, sodium, and chloride, all very soluble species, were at about the same levels in both wastes and in both laboratory and field circumstances.

6.0 COMPOSITION AND LEACHING CHARACTERISTICS OF TYPICAL LANDFILL SUBSTRATE MATERIALS

As noted in Section 5.0, it is likely that most FBC wastes that are generated in the future will be classified as nonhazardous, at least with respect to toxicity, and will therefore be disposed of in a nonsecure landfill. Thus, leachate will probably not be contained but will interact with the natural soils and geological substrate at future disposal sites. Samples of six geological substrate materials (termed "disposal media" here) that are typical of future landfill sites were obtained from the area around the Crown, West Virginia field site.

The composition and leaching characteristics of the six types of disposal media obtained were determined to provide information to help understand the attenuation (or mobilization) of contaminants in FBC waste leachate when exposed to the disposal media and to provide a basis for comparing the quality of FBC waste leachate with the leachate from the natural earth materials. The sources of the disposal media samples are given in Section 3.0. The composition, physical properties, and leaching characteristics of the disposal media are described in this section; the interaction of the disposal media and FBC waste leachate (attenuation and mobilization of dissolved species) is described in Section 6.0.

6.1 Disposal Media Composition

The methods used to determine the composition of the disposal media were similar to those used for the FBC waste. The mineral components were identified, and the elemental composition was determined by sample digestion and analysis of the digest solution. In addition, the cation exchange capacity and proximate and ultimate analyses were determined for each of the six disposal media. The details of the disposal media composition and a description of the methods of analyses are given in Appendix C.

6.1.1 Mineralogical Composition

The mineral components of each of the disposal media were determined both by binocular microscope examination and by X-ray diffraction (XRD) analysis of powdered samples.

Shale

Binocular microscope examination showed that the shale samples were composed of three different types of material. The identifiable minerals in all three types consisted primarily of quartz grains. Muscovite, hematite, and an unidentified black mineral were also seen. The clay minerals could not be identified with the binocular microscope.

The XRD patterns of the shale samples were somewhat difficult to interpret because of the large number of minerals present and the resulting complexity of the patterns. The principal identifiable minerals were quartz, kaolinite, montmorillonite, illite, chlorite, and muscovite. The patterns also indicated that vermiculite, nontronite, phlogopite, enstatite, diopside, and augite were present.

Interburden

Binocular microscope examination of the interburden showed that it was composed of about 40% coal fragments. The remainder was found to be more than half quartz grains. Mica (muscovite and biotite) was also abundant, and gypsum and tourmaline were observed in small quantities. The XRD analysis found essentially the same suite of minerals as were observed in the shale sample, with quartz, kaolinite, montmorillonite, illite, chlorite, and muscovite as the primary constituents.

Sandstone

Under the binocular miscroscope, the sandstone sample was found to consist of three different types of material. One type was white in color and appeared to be about 95% quartz with some muscovite and white cement. A second type was dark gray and was composed of quartz, organic material, and mica. The third sandstone type was silver-gray and contained about 80% quartz and lesser amounts of biotite, muscovite, and unidentified opaque minerals. The XRD analysis again resulted in a complex pattern very similar to that obtained from the shale samples. The principal minerals indicated were quartz, kaolinite, montmorillonite, illite, chlorite, and muscovite.

It is apparent that the shale, interburden, and sandstone, all of which came from the same coal mine (Christopher No. 3 mine in Monongalia County, West Virginia), have very similar composition and differ primarily in the relative abundance of quartz, coal fragments, and clay minerals.

Glacial Till

The glacial till, under microscope examination, was found to consist of about one-third limestone particles and two-thirds particles of varying composition, including mudstone, granite, schist, dolomite, sandstone, and other rock and mineral particles. A small amount of plant material was also observed. The XRD pattern for the glacial till revealed the presence of quartz, calcite, dolomite, illite, and other less important minerals.

Alluvium

Under the microscope, the alluvium was found to consist primarily of quartz with about 5% mica, siltstone, sandstone, limestone, dolomite, and other types of rock fragments. XRD analysis revealed the presence of quartz, plagioclase, and muscovite.

Limestone

Microscopic examination of a thin section of the limestone revealed that it consisted of sparry calcite and fossiliferous pellet rock. XRD analysis showed that the principal mineral components were calcite, quartz, dolomite, illite, and mica.

6.1.2 Chemical Composition

The chemical compositions of the disposal media were determined by the same methods as were used for the FBC wastes. The samples were digested by various methods and the composition of the digest solution was determined. Samples of fresh disposal media (before exposure to FBC waste leachate) and "burdened" media (after exposure) were analyed. Analyses of the "burdened" media were performed on samples that were exposed to Exxon PFBC waste leachate and on samples exposed to Alliance AFBC leachate. These burdened samples were from Step 4 and repetitions of Step 5 of the laboratory batch equilibration protocol.

The results of the chemical analysis of the disposal media are shown in Table 6-1. The principal elements of concern for which the analysis were performed were Si, Al, Fe, K, Ca, Mg, Na, and SO_4. The shale, interburden, sandstone, glacial till, and alluvium were generally similar in composition and in particular had a high percentage of silicon and aluminum, as would be expected since they are aluminosilicate rock materials. Likewise, limestone had high calcium content which reflects its primarily calcium carbonate composition. The lower silicon content of interburden relative to the other rock types reflects the high percentage of coal fragments present in the sample. The glacial till had a higher calcium content than the other aluminosilicate samples because it was a high lime till that reflected the bedrock composition from which the glaciers formed the till.

TABLE 6-1. PRINCIPAL COMPONENTS OF THE DISPOSAL MEDIA BEFORE AND AFTER EXPOSURE TO FBC WASTE LEACHATE[1]

	Shale			Interburden			Sandstone			Glacial Till			Alluvium			Limestone		
Element/ Species	Fresh	EPFBC[2]	AAFBC[3]	Fresh	EPFBC[2]	AAFBC[3]	Fresh	EPFBC[2]	AAFBC[3]	Fresh	EPFBC[2]	AAFBC[3]	Fresh	EPFBC[2]	AAFBC[3]	Fresh	EPFBC[2]	AAFBC[3]
Si	25	22	21	18.7	16.7	25.0	26	16.6	25	23	21	20	35	32	32	4.1	4.0	4.4
Al	9.4	8.4	6.9–7.2	9.9	8.9	7.7	9.5	8.0	6.9	6.2	5.8	4.7	4.1	3.9	3.1	1.47	1.42	1.30
Fe	4.3	2.4	2.4	2.3	2.0	2.5	4.3	3.4	3.9	3.4	3.0	3.7	3.0	2.7	3.3	0.72	0.70	0.82
K	2.8	2.4	2.4	1.66	1.42	1.43	3.0	2.4	2.4	2.4	2.1	2.2	1.2	1.09	1.08	0.75	0.63	0.65
Ca	1.12	4.2	3.6	0.53	2.86	2.4	0.39	2.8	2.7	5.7	8.3	7.5	0.141	2.5	2.0	32	32	29
Mg	0.85	0.77	1.03	0.4	0.37	0.47	0.75	0.62	0.87	1.7	1.6	2.1	0.30	0.29	0.37	1.09	1.07	1.49
Na	0.31	0.3–0.8	0.3	0.63–0.74	0.58 – 0.76	0.22	0.30	0.32–0.91	0.33	0.46	0.41	0.41	0.37	0.94	0.39	0.13	0.12	0.15–0.40
SO_4	0.37	2.6	3.07	0.64	2.3	2.45	0.53	2.6	3.3	<0.1	2.2	2.7	<0.1	2.0	2.3	0.12	1.33	1.29

[1] Units are weight percent.

[2] Disposal media after exposure to Exxon PFBC waste leachate in Steps 4 and 5 (6 repetitions) of the lab protocol.

[3] Disposal media after exposure to Alliance AFBC waste leachate in Steps 4 and 5 (9 repetitions) of the lab protocol.

Relative to the fresh disposal media samples, the burdened samples showed generally slightly lower Si, Al, Fe, and K percentages. This apparent depletion may be caused both by leaching which occurred during exposure to the FBC waste leachate and by an apparent decrease that occurred because of the addition of other components to the solids from the leachate.

All disposal media showed an increase in calcium (except limestone) and sulfate after exposure to the FBC waste leachate. For calcium, the increase was greatest for the interburden (from 0.5% to about 2.6%), sandstone (0.4% to 2.8%), and alluvium (0.1% to 2.3%). There was no significant difference in the amount of calcium added to the disposal media for the Exxon PFBC and Alliance AFBC waste leachates. For sulfate, the change in percentage was from less than 1% to more than 2% for all media except limestone. Slightly more sulfate was added to the media samples by Alliance AFBC than by Exxon PFBC waste leachate.

6.1.3 Cation Exchange Capacity

The interburden sample had the highest cation exchange capacity with a value of 51 milliequivalents (meq) per 100 g of sample. Shale, glacial till, and alluvium all had comparable values of 36-37 meq/100 g. Limestone and sandstone had cation exchange values of about 30 and 31 meq/100 g, respectively.

6.1.4 Proximate Analysis

The principal finding of the proximate analysis of the disposal media was the presence of a small amount of heating value in the shale, interburden, and sandstone, which reflects their coal mine origin. Interburden had the highest value, with about 3000 Btu/lb, and the shale had lower values, with about 250 and 150 Btu/lb, respectively. As noted, the interburden consisted of about 40% coal fragments. The other disposal media samples had no appreciable heating value.

The ash content of all the media except the interburden and limestone was about 90% or more. The interburden had an ash content of about 70% and a fixed carbon content of 14%. The limestone had a 64% ash content and a 9% fixed carbon content. The fixed carbon content of the other media was nil. The percent volatile content was quite uniform at 10-15% except for alluvium, which was lower (3%), and limestone, which was higher (27%). Exposure to Exxon PFBC and Alliance AFBC waste leachate generally had little or no effect on the proximate analyses of the disposal media samples.

6.2 Physical Properties of the Disposal Media

The principal physical properties determined for the disposal media were the particle size distribution, specific gravity, and specific surface area. In addition, the particle shape and surface characteristics were examined by use of the scanning electron microscope. Appendix B contains the details of the physical properties of the disposal media.

6.2.1 Particle Size Distribution

The particle size distribution was obtained for the three consolidated disposal media (interburden, till, and alluvium) by sieve and pipette analysis. The alluvium contained mostly coarse silt with some very fine sand and about 10% clay material. The median grain size was about 100 microns. The interburden had a higher fine sand content than the alluvium and contained about 21% clay. The median grain size of the interburden was about 40 microns. The glacial till was more fine grained than the other two media, with a median grain size of about 10 microns and about 39% clay-size particles. Grain size distribution curves for these media are shown in Appendix B. Particle size characteristics were not obtained for the consolidated disposal media because the grain size of the samples depended on the degree of crushing of the sample during sample collection rather than being a property of the media.

Most of the disposal media were analyzed for average particle size after the samples were ground to the same extent as they were in the preparation for the laboratory batch equilibration protocol (see Appendix D). The analysis was performed by the SediGraph Particle Size Analyzer. The ground samples of sandstone and shale had the largest "equivalent sphere diameter", with 8.2 and 7.4 microns respectively. The limestone and glacial till had comparable sizes, with 3.6 and 3.2 microns, respectively.

All disposal media samples were examined by binocular microscope to obtain qualitative descriptions of the textural relationships and to further describe the grain sizes present. The shale was observed to range from clay shale to siltstone in grain size and was poorly sorted. It was fissile (broke up into small, plate-like pieces) and exhibited a laminar appearance. The interburden was found to be a poorly sorted, fissile mud shale with abundant coal fragments. The sandstone was a clayey fine sandstone with moderate sorting.

The glacial till was a very poorly sorted granular mud. The alluvium was found to consist of poorly sorted, slightly gravelly silty fine sand. The limestone, upon examination by polarizing microscope, was determined to consist of grains with the pore space between filled with crystalline calcite. The rock thus formed was well consolidated.

6.2.2 Specific Gravity and Specific Surface Area

The specific gravities of the shale, sandstone, glacial till, and alluvium were quite comparable and ranged from 2.72 to 2.77. The limestone was somewhat higher at 2.81, and the interburden was considerably lower at 2.25. The lower specific gravity of the interburden was probably caused by the high proportion of coal fragments.

The specific surface areas of the ground disposal media ranged from 5.5 m^2/g to 23.8 m^2/g. The sandstone, alluvium, and limestone had specific surface areas in the 8 to 10 m^2/g range, whereas the shale, interburden, and glacial till had specific surface areas of 15 to 24 m^2/g. The expected inverse relation between specific surface area and particle size was observed for three of the four ground disposal media for which grain size data were obtained. Limestone, however, showed both small grain size and low specific surface area.

6.2.3 Particle Shape and Surface Characteristics

Scanning electron photomicrographs were obtained for each of the disposal media at two magnifications. These micrographs generally corroborated the findings of the X-ray diffraction and binocular microscope studies and the solids composition determinations. The observed particles generally had shapes and surface characteristics consistent with the mineral composition of the disposal media samples.

The shale, interburden, and sandstone samples exhibited large, irregular flakes with smaller crystals on the flakes. This characteristic is normally observed for clay-bearing rock samples. The most crystalline sample was the limestone, which would be expected of a ground calcium carbonate rock. The individual crystals observed were probably calcite. The appearance of the glacial till was similar to that of the limestone, but the individual particles were somewhat larger. The alluvium was found to consist primarily of platelets, which is not entirely in accordance with the predominantly quartz composition noted in the binocular microscope and X-ray diffraction studies.

Scanning electron micrographs were also obtained for the shale and sandstone after leaching for seven days according to the Step 1 and 2 procedures of the batch equilibration protocol. The visual appearance of these samples did not differ substantially from the appearance of unleached samples.

6.3 Leaching Characteristics of the Disposal Media

The leaching characteristics of the disposal media were determined to provide a basis of comparison between leachates derived from FBC wastes and leachate derived from natural geological materials and to gain insight into which species are likely to be mobilized rather than attenuated when FBC waste leachate is exposed to disposal media. The disposal media leaching characteristics were determined by laboratory protocol leaching, in field control cells, and in laboratory control columns.

6.3.1 Protocol Step 1 Leaching of the Disposal Media

Protocol Step 1 was performed on each of the disposal media with deionized water as the eluant; the concentrations of the various parameters in the Step 1 leachate are shown in Table 6-2. Overall, the highest concentrations were noted for TDS, SO_4, Ca, Mg, K, and Na. The pH values ranged from slightly acid (5.5) to slightly alkaline (8.7). For most parameters, the alluvium leachate had lower concentrations than leachates from the other media.

Table 6-3 shows for several parameters the weight percent of species leached from the disposal media during Step 1 leaching. Sulfate removal was quite high for all media, especially the glacial till, alluvium, and limestone. Molybdenum and cobalt leaching was high for the two media for which data are available, shale and interburden. The percent of calcium leached was substantial for sandstone and alluvium. Moderate amounts of Cr, Cu, Sr, Na, and Zn were leached from all media. Calcium removal from the shale was moderate, and magnesium leaching was moderate for all media except glacial till.

6.3.2 Laboratory Column Leaching of the Disposal Media

As noted, the six laboratory columns containing only disposal media were about six feet long and six inches in diameter. The columns were operated for 517 days, during which time 63 leachate samples were collected

TABLE 6-2. CONCENTRATIONS OBSERVED IN LEACHATES FROM PROTOCOL STEP 1 EXTRACTIONS OF DISPOSAL MEDIA

Element/ Species	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Al	<0.25	<0.25	<0.25	<0.25	<0.25	~0.30
B	0.06	~0.07	<0.045	~0.05	<0.045	<0.045
Ba	0.12	0.092	0.056	0.14	0.071	0.12
Ca	52	28	73	22	1.0	9.9
Cd	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Cl	<2.0	<2.0	<2.0	<2.0	<2.0	4.1
Co	<0.03	0.15	~0.04	<0.03	<0.03	<0.03
Cr	~0.015	0.088	<0.005	<0.005	<0.005	<0.005
Cu	<0.005	0.088	0.005	<0.005	<0.005	<0.005
F	0.39	0.13	0.34	1.03	0.09	1.05
Fe	0.055	0.24	<0.04	<0.04	<0.04	<0.04
K	4.7	4.8	7.8	<0.22	<0.21	7.8
Li	~0.006	0.034	0.035	<0.002	<0.002	<0.002
Mg	7.1	9.7	22	4.4	<0.17	2.6
Mn	0.13	0.19	0.63	<0.006	0.03	<0.006
Mo	<0.01	<0.01	<0.01	~0.015	<0.01	~0.20
Na	2.1	1.4	1.6	3.5	1.6	12.5
Ni	0.070	0.26	<0.015	<0.015	~0.02	0.033
pH[2]	8.0	5.5	7.7	8.2	5.9	8.7
Si	3.7	14	4.9	3.9	5.5	3.4
SO_4	68	138	172	15	4.5	45
Sp. Cond.[3]	350	300	500	150	40	210
Sr	0.13	0.20	0.18	0.007	<0.002	0.33
TDS	165	230	428	~40	15	128
Ti	<0.025	<0.025	0.05	<0.025	<0.025	<0.025
TIC	24.0	2.0	21.0	14.0	<2.0	12.0
TOC	2.0	0.62	0.70	4.7	2.3	1.2
V	<0.015	<0.015	0.020	<0.015	<0.015	<0.015
Zn	~0.020	0.255	0.015	~0.015	<0.015	<0.015

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[1] Concentrations are in mg/L unless otherwise noted. Values indicated are averages of two values.

[2] Units are standard pH units.

[3] Units are microm hos/cm.

TABLE 6-3. WEIGHT PERCENT OF TOTAL SOLIDS CONTENT LEACHED FROM THE DISPOSAL MEDIA DURING PROTOCOL STEP 1 LEACHING[1]

Element/ Species		Percent of Total Leached					
		Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Al	A	–	–	–	–	–	–
	B	0.0035	0.0033	0.0035	0.0053	0.008	0.022
B	A	0.12	0.34	0.30	0.63	0.072	0.42
	B	0.15	0.45	0.40	0.83	0.096	0.56
Ba	A	0.19	0.098	0.18	0.32	0.17	1.6
	B	0.21	0.11	0.20	0.35	0.71	1.7
Be	A	0.4	0.52	0.34	0.51	0.59	1.7
	B	0.67	0.86	0.57	0.85	0.98	2.8
Ca	A	2.8	0.0059	8.2	0.55	22	0.10
	B	2.7	0.0057	8.0	0.53	21	0.10
Co	A	4.9	6.6	–	–	–	–
	B	7.5	10	–	–	–	–
Cr	A	0.72	0.56	0.74	0.89	1.1	1.2
	B	0.81	0.81	1.1	1.3	1.6	1.7
Cu	A	1.2	0.89	1.1	1.0	1.5	1.6
	B	1.3	0.92	1.2	1.1	1.6	1.7
Fe	A	0.0035	0.63	0.0034	0.0043	0.0049	0.02
	B	0.0035	0.63	0.0034	0.0043	0.0049	0.02
K	A	0.23	0.38	0.21	0.26	0.53	0.84
	B	0.23	0.37	0.21	0.26	0.52	0.83
Li	A	0.55	0.24	0.44	1.5	0.75	–
	B	0 54	0 24	0.43	1.5	0.74	–
Mg	A	1.1	2.3	1.3	0.55	3.1	0.85
	B	1.1	2.2	1.2	0.53	3.0	0.82
Mn	A	0.33	0.075	0.48	0.48	0.40	1.37
	B	0.31	0.071	0.45	0.45	0.38	1.31
Mo	A	13.8	13.2	–	2.2	–	–
Na	A	1.4	0.61	1.4	0.91	1.2	3.3
	B	1.1	0.48	1.1	0.73	0.90	2.6
Ni	A	2.5	2.0	2.8	2.5	5.7	7.9
	B	2.1	1.7	2.3	2.1	4.8	6.7
Si	A	2.4	0.03	0.02	0.03	0.02	0.14
	B	2.5	0.03	0.02	0.03	0.02	0.14
SO_4	A	21	12	14	<74	<74	62
	B	20	11	14	<73	<73	61
Sr	A	1.0	0.96	1.6	1.3	2.4	0.46
	B	1.00	3.8	6.2	5.2	9.5	1.8
Ti	A	0.01	0.02	0.02	0.03	0.02	0.09
V	A	0.30	0.28	0.28	0.28	0.43	0.45
Zn	A	1.5	1.6	0.15	0.16	0.27	0.44
	B	1.5	1.5	1.5	1.6	2.7	4.3

[1] Values shown are for A and B replicates.

and analyzed. The concentration trends with time were evaluated for each parameter and for each column using computer printer plots of the leachate concentration data. A summary of the concentration ranges and trends over the leaching period is given in Table 6-4.

For all columns, the highest concentrations were noted for Ca, K, Mg, Na, Si, SO_4, and TDS. The leachates from the interburden-bearing column had higher concentrations of most parameters than the leachates from the other columns. The pH was much lower for the interburden column also. The limestone column had elevated fluoride and sodium values relative to the other columns. The alluvium column was lower than the other columns for many parameters, notably Ca, K, Mg, SO_4, and TDS.

Comparison of Table 6-4 with Table 6-3 shows that for most parameters and most columns, the lab control columns yielded generally higher concentrations in individual aliquots than Step 1 batch leaching of the disposal media. Except for Ba, Ca, and Cl (and a few individual species for one or two disposal media only), the column leachates were generally a factor of five (or much more) higher in concentration than the Step 1 batch leachates. The volume-per-mass ratio for the lab control columns was much less than 1, the ratio for Step 1 was 10.

6.3.3 Field Cell Leaching of the Disposal Media

Two field cells, Cell 7 containing shale and Cell 12 containing alluvium, were constructed and operated as control cells (without any waste) to provide a basis of comparison of leachates from the cells that did contain waste. The summary statistics for the concentrations of leachates from these two cells are shown in Table 6-5 for the shale-bearing cell and in Table 6-6 for the alluvium-bearing cell. The data included in the preparation of these tables were for the leachates collected after the first 60 days of cell operation.

TABLE 6-4. SUMMARY OF CONCENTRATION RANGES AND TRENDS OF LEACHATE FROM THE LABORATORY CONTROL COLUMNS CONTAINING DISPOSAL MEDIA ONLY

Element/ Species	Shale		Interburden		Sandstone		Glacial Till		Alluvium		Limestone	
	Concentration Range (mg/L)	Trend	Concentration Range (mg/L)	Trend	Concentration Range (mg/L)	Trend	Concentration Range (mg/L)	Trend	Concentration Range (mg/L)	Trend	Concentration Range (mg/L)	Trend
Al	0.6–6	↱	1500–2430	↓	0.6–3.3	↑	0.2–3.2	↷	1.6–2.9	↓	0.08–3.7	↷
B	0.3–2.3	↷	9–20	↓	0–2.4	↷	0–2.1	↷	0–1.8	↓	0.6–2.7	↷
Ba	0.04–0.3	⇣	0–0.16	↓	0–0.6	↷	0.1–0.9	⤴	0.06–0.76	↷	0.05–0.95	↷
Ca	600–1200	↓	400–574	↑	740–860		210–320	↷	12–28	↓	100–330	↓
Cd	0.04(1)*		1.1–2.9	↷	DL		DL		DL		0.29(1)*	
Cl	0–3.5	↑	15		0–4	↑	0–6.5	↑	<2		<2	
Co	0.3–0.5	↳	16–40	↓	0–0.16	↷	0–0.24	↷	0–0.27	↷	0–0.9	↷
Cr	0.16–0.5	↷	0–7.2	↷	0.05–0.3	↷	0.015–0.40	↷	0–0.4	↷	0.03–0.29	↷
Cu	0–0.4	↷	26–56	↓	0–0.2	↷	0–0.34	↷	0–0.35	↷	0.005–0.18	↷
F	0.1–0.6	↳	2–15	↳	0.06–0.9	↳	0.3–0.7	↳	0.04–0.15		1.3–1.9	
Fe	0.06–2.9	↓	6500–8200		0.05–1.5		0.25–3.27	↷	0.2–7.6	↓	0.25–2.7	↓
K	68–340	↳	50–850	↓	40–200	↓	15–75	↳	5–9	↷	25–141	↓
Mg	0–630	↳	1150–2300	↓	80–220		46–85	↷	5–7	↷	61–107	↷
Mn	20–50	↳	34–67	↷	0.1–2	⤴	0.3–3.4	↷	0.18–1.8	↳	0.12–1.1	↷
Mo	0.05–0.32	↷	1–10	↓	0.025–0.18	↷	0.01–0.32	↷	0–026	↷	0.8–1.3	↓
Na	17–41	⇣	0–130	↷	7–11		0.6–31	↱	3–5		227–721	↷
Ni	0–0.5	⤴	28–80	↓	0–0.14	⤴	0–0.08	↳	0–0.09		0–0.1	↓
pH[1]	7–8	↳	1.9–2.4		7–8		7.2–8.2		4–8		7.5–8.5	
Si	7–17	↷	72–145	↷	10–25	↳	19–39	⤴	9.6–17	↓	11–43	↷
SO_4	1900–2900	↱	18000–58000	↓	1500–2000	↱	201–560	↳	18–30		390–4370	↳
Sp. Cond.[2]	3000–11000	↷	10000–30000	↳	2600–4100	↳	800–1400	↳	95–120		1000–7000	↓
Sr	1.8–6	↳	0.6–1.4	↳	1.6–2.6	↳	0.3–0.9	↳	0.11–0.44	↓	6.4–8.2	
TDS	4000–13600	↳	28000–90000	↓	3000–4950	↳	560–1200	↳	60–295		820–7800	↳
Ti	0.03–1.1	↷	0.15–1.0	↷	0.01–0.65	↷	0–0.97	↷	0–1.0	↷	0–1.1	↷
TOC	0–6.8		0–40	↓	0–12	↓	0–100	↓	0–30	↓	0–24	↳
V	0.4–0.9	↷	1.1–8.2	↷	0.3–0.5	↷	0.13–0.67	↷	0.5–0.7	↷	0.19–0.70	↷
Zn	0.02–0.5	↷	86–143	↓	0.02–0.09	⤴	0–0.9	↷	0–0.19		0–0.12	↷

Symbols:
↑ – increase
↓ – decrease
⇡ ⇣ – net change with variation
No indicator means relatively constant.
↷ – reversal downward
⤴ – reversal upward
↳ – decrease with leveling out
↱ – increase with leveling out
DL – detection limit
* – only one measurable value

[1] Units are standard pH units.

[2] Units are micromhos/cm.

NOTE: The indicated zero values are actually detection limit values for the various species.

TABLE 6-5. SUMMARY STATISTICS FOR CONCENTRATIONS OF LEACHATES FROM THE FIELD CONTROL CELL CONTAINING SHALE (CELL 7)[1]

Element/ Species	Number of Observations	Mean	Median	Minimum	Maximum	Range	Standard Deviation
Al	15	2.1	1.8	0.15	4.2	4.1	1.2
B	15	1.7	1.1	0	7.2	7.2	2.0
Ba	15	0.25	0.17	0	0.93	0.93	0.28
Be	8	0	0	0	0.01	0.01	0.002
Ca	15	1000	670	580	3290	2710	830
Cd	15	0.04	0.02	0	0.24	0.23	0.06
Cl	9	1.4	1	1.0	3.3	2.3	0.9
Co	15	0.08	0.03	0	0.39	0.39	0.11
Cr	15	0.15	0.08	0	0.71	0.71	0.20
Cu	15	0.10	0.04	0	0.91	0.91	0.23
F	15	0.19	0.20	0.10	0.28	0.18	0.05
Fe	15	0.07	0.04	0	0.23	0.22	0.07
K	15	66	50	11	230	220	63
Li	8	0.03	0	0	0.11	0.11	0.046
Mg	15	214	205	0.03	310	310	73
Mn	15	0.08	0.03	0	0.33	0.33	0.11
Mo	15	0.09	0.05	0	0.49	0.49	0.13
Na	15	6.1	7.1	0	10	10	3.0
Ni	14	0.14	0.10	0.01	0.73	0.72	0.20
pH[2]	15	7.3	7.3	6.9	7.6	0.7	0.22
Si	15	15	9.9	5.4	42	37	11.6
SO_4	15	2060	2060	1890	2250	360	120
Sp. Cond.[3]	15	3170	3150.00	2880.00	3580.00	700.00	220
Sr	15	1.8	1.5	1.2	3.2	2.0	0.6
TDS	15	3670	3630	3260	4170	910	240
Ti	15	0.19	0.04	0	0.99	0.99	0.30
TIC	2	75	75	71	79	8	5.7
TOC	5	8.9	8.9	4.1	15	11	4.1
V	15	0.25	0.15	0	0.81	0.81	0.28
Zn	15	0.30	0.17	0.01	1.50	1.49	0.40

[1] Units are mg/L unless otherwise noted.
[2] Units are standard pH units.
[3] Units are micromhos/cm.

TABLE 6-6. SUMMARY STATISTICS FOR CONCENTRATION OF LEACHATE FROM THE FIELD CONTROL CELL CONTAINING ALLUVIUM (CELL 12)[1]

Element/ Species	Number of Observations	Mean	Median	Minimum	Maximum	Range	Standard Deviation
Al	15	0.69	0.63	0.03	1.6	1.6	0.50
B	15	0.61	0.093	0.002	2.7	2.7	0.94
Ba	15	0.32	0.26	0.007	0.96	0.95	0.30
Be	8	0	0	0	0	0	0
Ca	15	79	30	9.3	590	580	150
Cd	15	0.033	0.012	0.002	0.22	0.22	0.06
Cl	7	1.0	1.0	1.0	1.0	0	0
Co	15	0.06	0.02	0.003	0.37	0.36	0.09
Cr	15	0.083	0.012	0	0.55	0.55	0.15
Cu	15	0.03	0.005	0	0.1	0.1	0.03
F	15	0.12	0.1	0.06	0.3	0.24	0.06
Fe	15	0.036	0.019	0.004	0.20	0.20	0.051
K	15	5.7	2.3	1.0	20	19	7.4
Li	8	0.007	0.001	0	0.05	0.05	0.02
Mg	15	13	6.2	0.11	86	86	22
Mn	15	0.38	0.23	0.001	1.2	1.2	0.37
Mo	15	0.054	0.012	0.001	0.44	0.44	0.11
Na	15	3.4	3.6	0.003	6.0	6.0	1.5
Ni	14	0.11	0.023	0.007	0.72	0.71	0.20
pH[2]	15	6.4	6.4	5.7	7.2	1.6	0.43
Si	15	14	8.6	5.1	33	28	9.7
SO_4	15	130	55	29	660	630	170
Sp.Cond.[3]	15	320	230	104	1020	920	290
Sr	15	0.2	0.14	0.07	0.75	0.68	0.18
TDS	15	320	160	90	1330	1240	340
Ti	15	0.13	0.012	0.001	0.80	0.80	0.23
TIC	3	13	14	1.0	23	22	11
TOC	5	7.2	7.7	4.3	10	5.7	2.5
V	15	0.04	0.009	0.001	0.17	0.17	0.06
Zn	15	0.15	0.05	0.006	1.1	1.0	0.27

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[1] Units are mg/L unless otherwise noted.

[2] Units are standard pH units.

[3] Units are micromhos/cm.

In leachates from the shale-bearing field control cell, concentrations were highest for SO_4, Ca, Mg, K, and TDS. Other parameters having substantial concentration were TIC, TOC, Si, Na, Al, and Cl. The pH was very close to neutrality. For the alluvium field cell, the highest concentrations were noted for SO_4, Ca, TDS, Si, Ca, Mg, TIC, and TOC. Potassium and sodium also had substantial concentrations. The pH of the alluvium cell was slightly acid (6.4). The alluvium field cell in general had lower overall concentration that the shale cell; the TDS concentration for the shale cell was more than 10 times the TDS value for the alluvium cell.

6.3.4 Batch Leaching of the Burdened Disposal Media

During the initial phases of the program, disposal media from protocol Step 4, which had previously been exposed to Step 1 leachate for seven days, were placed in contact with deionized water ("Step 7"). The purpose of this step was to determine if an attenuating medium which has removed species from an FBC waste leachate will release these species to fresh water at a later time. The burdened media was leached in Step 1 and Step 2 fashion; that is, several repetitions of the steps, with seven days of leaching for each repetition. Four of the disposal media types were leached in this manner. Table 6-7 shows the concentration trends observed in the leachates thus generated and shows also the maximum concentration observed for each parameter.

Ca, Na, Sr, and SO_4 decreased consistently with repetitions of "Step 7" for all media. Silicon decreased slightly, and chromium decreased overall but occassionally increased in the intermediate steps. Copper increased moderately with repeated leaching, but erratic variation was seen. The pH values were moderately to strongly basic in the first leaching and decreased with repetitions of the leaching, but never below neutrality (pH = 7). Overall, the highest concentrations were noted for sulfate and calcium. Na, Al, B, and Si also had significant concentrations.

TABLE 6-7. CONCENTRATION TRENDS AND MAXIMA FOR SPECIES LEACHED FROM BURDENED DISPOSAL MEDIA[1]

Medium Element/ Species	Shale		Interburden		Sandstone		Limestone	
	Trend	Maximum	Trend	Maximum	Trend	Maximum	Trend	Maximum
Al	Steady increase	5.3	Increase net decrease	2.3	Increase to decrease	4.1	Net decrease	1.1
As	Net increase	0.57	Increase	1.5	Increase	0.60	Increase	0.69
B	Increase	2.1	Increase net decrease	1.1	Net increase	1.5	Increase then decrease	9.0
Ba	Decrease	0.036	Net Increase	0.12	Net slight increase	0.11	Slight increase	0.086
Ca	Decrease	180	Decrease	170	Decrease	180	Decrease	160
Cr	Net decrease	0.19	Decrease	0.22	Decrease then increase	0.16	Decrease	0.15
Cu	Ultimate increase to non DL	0.02	Ultimate increase	0.021	Increase	0.025	Increase	0.02
F	Modest decrease	0.37	-	-	Decrease	0.47	Data incomplete	0.67
Fe	Fluctuates to increase	0.90	Fluctuates	0.12	Erratic	0.29	Erratic	0.16
Mg	Erratic	0.42	Fluctuates	0.042	Net increase	0.22	Increase	0.89
Mn	Erratic	0.030	Net increase	0.011	Erratic	0.005	Erratic	0.007
Na	Decrease	23	Decrease	23	Net decrease	23	Net decrease (erratic)	42
Ni	Erratic	0.11	Erratic	0.15	Erratic	0.20	Erratic	0.13
Pb	Occasional non DL[2]	0.09	1 non DL value	0.074	Erratic	0.17	Erratic	0.33
pH[3]	Decrease	to 9.3	Decrease min.	8.2	Decrease to min.	8.5	Decrease to min.	7.4
Si	Decrease	2.2	Decrease	2.2	Slight decrease	1.7	Slight decrease	1.6
Sp.Cond.[4]	Decrease	1020	Decrease	1280	Decrease	1160	Decrease	1120
SO_4	Decrease	220	Net decrease	160	Net decrease	220	Data incomplete	200
Sr	Decrease	0.54	Decrease	0.50	Decrease	0.45	Decrease	0.97
Ti	Erratic occasional Non DL	0.012	Slight increase	0.0095	Erratic	0.012	Erratic	0.023
V	-	-	~DL one value	0.019	DL one value	0.017	~DL (2 values)	0.025
Zn	Decrease	0.086	Erratic to increase	0.75	Decrease	0.10	Decrease	0.093

[1] Units are mg/L unless otherwise noted.

[2] DL = Detection Limit

[3] Units are standard pH units.

[4] Units are micromhos/cm.

7.0 ATTENUATION OF FBC WASTE LEACHATE BY NATURAL SUBSTRATE MATERIALS

The attenuation of FBC waste leachate when exposed to natural geological substrate material was evaluated in a variety of laboratory and field experiments. Although the term "attenuation" is used to describe the chemical changes in the leachate resulting from exposure to the disposal media, in actuality many species were mobilized from the media rather than attenuated. The term attenuation is used here as a shorthand reference for both attenuation and mobilization; the combined term attenuation/mobilization is used extensively in the appendices.

In the laboratory studies, attenuation was assessed in the batch equilibration protocol (Steps 4, 5, and 6). Attenuation was evaluated in the field studies by the leachate samples from the lower sample point. As noted in Section 3.0, six disposal media were used in the lab and field experiments -- shale, interburden, sandstone, glacial till, alluvium, and limestone.

In general, attenuation is described in terms of leachate concentration trends observed and by reference to a derived parameter termed fractional attenuation. For the lab protocol results, fractional attenuation is defined as follows:

$$A_L = \frac{C_i - C_f}{C_i}$$

where: A_L = laboratory fractional attenuation

C_i = initial concentration (before exposure to the disposal media)

C_f = final concentration (after exposure to the disposal media)

For the field cells, fractional attenuation is defined as follows:

$$A_F = \frac{C_U - C_L}{C_U}$$

where: A_F = field fractional attenuation

C_U = concentration in leachate from upper sample point

C_L = concentrations in leachate from lower sample point.

In the paragraphs that follow, each FBC waste is considered in turn relative to the attenuation characteristics of its respective leachate. At the end of this Section, a comparison is made of the relative degree of attenuation experienced among the three waste leachates for each disposal medium.

7.1 Attenuation of Exxon PFBC Waste Leachate

The attenuation of Exxon PFBC waste leachate was assessed by performance of Step 4, 5, and 6 of the batch equilibration protocol and in the six field cells. Attenuation of Exxon PFBC waste leachate in the lab leaching columns is described in Section 5.1.2.

7.1.1 Attenuation in the Batch Equilibration Protocol

A summary of the lab protocol results is given below; details are given in Appendix D.

7.1.1.1 Initial Attenuation: Protocol Step 4

During protocol Step 4, waste leachate which was generated during Step 1 (7-day) leaching of FBC waste was exposed to a known mass of disposal medium. The times of equilibration were 1, 2, and 7 days. An evaluation of the time of leaching showed that there was little difference among the leachates from the three times of extraction. Therefore, the seven-day equilibration data are used in this section. A detailed discussion of the effects of time of equilibration is given in Appendix D.

For the Exxon PFBC waste, the laboratory fractional attenuation was computed for each parameter by using an average concentration for all Step 1 leachates for the initial concentration (C_i). The exact value of the Step 1 concentration was not known for each individual aliquot used in Step 4, so the average of the concentrations observed in all Step 1 leachates was used in the computation of A_L. For this reason, the A_L values obtained for the Exxon waste are not as precise as for the Alliance and Georgetown AFBC wastes.

Table 7-1 contains a summary of the A_L values found for several parameters of interest. Attenuation of Exxon PFBC leachate by shale was positive for all parameters for which A_L could be determined; attenuation was greatest for Li, Mg, Al, B, and Cr. For interburden, attenuation was greatest for Li, Ni, B, Mg, and TOC. Chloride, sodium and fluoride were contributed to the leachate by the interburden. Exposure to the sandstone resulted in attenuation of all parameters for which A_L was calculated. Attenuation was greatest for Li, Mg, Na, B, and Zn. The least attenuation was noted for silicon and strontium.

Strongest attenuation during exposure to glacial till was noted for Li, Na, Mg, and B. Nickel was strongly contributed, and Al, Cr, and Si were also mobilized from the till. Exposure of the Exxon PFBC leachate to the alluvium resulted in mobilization of a number of parameters, including Al, Ba, Cr, Fe, and Si. Nickel was strongly attenuated. Mg, Na, B, and Zn were also substantially attenuated. For limestone, attenuation was greatest for

TABLE 7-1. SUMMARY OF STEP 4 LABORATORY FRACTIONAL ATTENUATION (A_L) VALUES FOR EXXON PFBC WASTE LEACHATE AND FOR EACH DISPOSAL MEDIUM

Element/ Species	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Al	0.95	0.56	*	−0.30	−0.60	−1.32
B	0.9	0.97	0.97	0.94	0.96	0.96
Ba	*	0.71	*	*	−0.42	−0.30
Ca	0.85	0.25	0.53	0.66	0.67	0.66
Cl	–	−1.1	–	–	–	–
Cr	0.95	*	0.34	−0.21	−0.47	−0.43
F	0.7	−0.19	0.64	0.20	0.65	0.11
Fe	*	0.47	0.86	0.73	−0.91	0.60
Li	1.0	1.0	1.0	1.0	0.72	0.60
Mg	1.0	0.97	1.0	0.99	1.0	0.99
Na	–	−0.32	1.0	1.0	1.0	0.66
Ni	–	1.0	–	−30	29	−38
Si	*	0.47	0.15	−2.5	−0.66	−0.71
SO_4	0.41	0.04	0.20	0.23	0.40	0.39
Sr	0.5	*	0.18	0.61	0.34	−0.14
TDS	0.6	0.36	0.33	0.48	0.67	0.44
TOC	–	−3.0	–	–	–	−1.40
Zn	*	*	0.95	0.92	0.91	0.86

NOTE: Each value is a mean of duplicate pairs. Dash indicates initial (Step 1) concentration values were at the detection limit.

* = One value was positive and one was negative, so no mean value is reported.

magnesium and boron. Silicon was highly mobilized, and several other parameters were also contributed somewhat, including Al, Ba, Cr, Si, Sr, and TOC.

Several parameters were substantially attenuated by all media, including B, Ca, Li, Mg, SO_4, and TDS. No parameter was consistently mobilized from all media, although Al, Cl, Cr, Ni, Si, and TOC were found to be mobilized in most of the disposal media for which A_L could be determined.

7.1.1.2 Repeated Exposure of Disposal Media to Fresh Leachate: Protocol Step 5

Protocol Step 5 involved the repeated exposure of a sample of disposal medium to fresh aliquots of leachates from Step 1 leaching of the Exxon PFBC waste. Six repetitions of Step 5 were performed. For each step, a value of A_L was computed, and plots were prepared showing A_L values as a function of volume per mass (VPM). The resulting plots were examined for several species of interest, and the trends were categorized in terms of increasing, decreasing, constant, and erratic behavior. The results of this analysis are shown in Table 7-2 for each type of disposal medium.

The trends in attenuation behavior varied from species to species and from disposal medium to disposal medium. The only species which showed consistent behavior were calcium, sulfate, and TDS (which would be expected to follow calcium and sulfate). All three of these species showed decreasing attenuation with successive Step 5 repetitions, with the exception of the sulfate trend for interburden. For most parameters, shale and interburden showed generally decreasing or constant attenuation with increasing volume-per-mass values. The alluvium and limestone yielded mostly erratic attenuation results. Sandstone and glacial till showed a mixture of decreasing, increasing, and erratic trends for the various species.

TABLE 7-2. TRENDS OF LABORATORY FRACTIONAL ATTENUATION (A_L) WITH SUCCESSIVE REPETITIONS OF PROTOCOL STEP 5 ON EXXON PFBC WASTE

Element/ Species	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Al	Decrease to erratic negative	Decrease to erratic negative	Decrease to erratic negative	Erratic	Erratic then negative	Erratic then negative
B	Constant	Decrease	Constant	Consistent decrease	Decrease	Decreasing positive
Ba	Decrease to erratic negative	Decrease to erratic negative	Decrease to erratic negative	Decrease to erratic negative	Erratic positive and negative	Increase then erratic decrease
Ca	Consistent decrease	Decrease	Decrease	Consistent decrease	Erratic decrease	Erratic decrease
Cr	Erratic decrease	Decrease to erratic negative	Decrease to erratic negative	Decrease to negative	Decrease to erratic negative	Erratic negative
F	Decrease	Increase to constant	Constant positive	Increase to constant	Consistent decrease	Erratic decrease
Fe	Constant positive	Constant positive	Constant positive	Decreasing positive	Erratic negative	Erratic positive
Na	Constant positive	Decrease	Erratic positive	Decrease to negative	Erratic positive	Erratic negative
Si	Erratic	Erratic	Erratic positive	Erratic	Erratic negative	Erratic negative
SO_4	Consistent decrease	Increase to zero	Consistent decrease	Consistent decrease	Consistent decrease	Decrease to erratic negative
Sr	Decrease then increase	Decrease then increase	Erratic positive	Decrease	Erratic positive	Erratic positive
TDS	Consistent decrease	Consistent decrease	Decrease to negative	Consistent decrease	Decrease to erratic negative	Decrease to erratic negative
Zn	Constant positive	Increase from zero	Constant positive	Decrease	Decreasing positive	Erratic

7.1.1.3 Repeated Exposure of Leachate to Fresh Disposal Media: Protocol Step 6

During protocol Step 6, leachate from Step 4 was re-exposed to a fresh sample of disposal medium repeatedly to evaluate the continued uptake (or release) of contaminants in the leachate with such repeated exposure. For the Exxon PFBC waste leachate, Step 6 was repeated five times. For each species, a plot of the fractional attenuation as a function of Step 6 repetition (decreasing volume per mass) was prepared and interpreted; the observed trends for each species and each disposal medium are shown in Table 7-3.

Calcium consistently showed decreasing attenuation generally from large or medium positive values to small positive, zero, or small negative values. Sulfate, strontium, and TDS also showed declining attenuation, although the beginning and ending values were variable. The other parameters showed highly variable or erratic attenuation behavior trends. None of the disposal media types produced consistent attenuation behavior for the various species.

To further investigate the effect of Step 6 replication on leachate behavior, concentration was plotted as a function of volume per mass, and the trends were categorized in terms of decrease, increase, or variable. The results of this analysis are summarized for the Exxon PFBC waste in Table 7-4. The parameters which showed a general decrease in concentration for most disposal media were Cr, F, Mo, pH, and Ti. Mn, Na, Si, and SO_4 showed an increase, and potassium remained constant. Other parameters behaved differently when the leachate was exposed to different media. The behavior trends were also not consistent for several parameters for any of the disposal media.

7.1.2 Attenuation in the Field Cells

Leachate attenuation in the Exxon PFBC field cells was evaluated by examining the data in three ways: (1) preparing plots of concentration of

TABLE 7-3. TRENDS OF LABORATORY FRACTIONAL ATTENUATION (A_L) WITH SUCCESSIVE REPETITIONS OF PROTOCOL STEP 6 ON EXXON PFBC WASTE

Element/ Species	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Al	Erratic	Large positive then erratic negative	Erratic large negative and positive	Erratic	Erratic	Large increasing positive
B	Erratic positive then small negative	Large positive then medium negative	Large positive then medium negative	Large positive then small positive	Large positive then negative	Large positive decreasing to large negative
Ba	Erratic then large negative	Erratic positive and negative	Erratic large positive and negative	Large positive then erratic negative	Medium negative then small positive and	Zero then erratic positive and negative
Ca	Large positive then small negative and positive	Medium positive then small negative	Medium positive then small negative	Large positive then zero	Large then small positive	Large then small positive
Cr	Erratic positive and negative	Erratic positive and negative	Erratic large positive then negative	Erratic positive then negative	Erratic	Erratic negative then positive
F	Large positive decreasing to small positive	-	Large positive then small positive and negative	Small positive	Erratic large positive	Small positive then small negative
Fe	Erratic negative then positive	Erratic	Erratic positive and negative	Erratic	Erratic large negative then medium positive	Erratic positive to erratic negative
Na	Small positive then small negative	Small negative then small positive	Erratic small positive	Erratic negative	Small positive to small negative	Medium positive to medium negative
Si	Large negative then small positive and negative	Large then small negative	Erratic positive and negative	Large negative then small negative	Large negative then small negative	Medium then large then small negative

(continued)

TABLE 7-3. (Continued)

Element/ Species	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
SO_4	Large positive then small negative	Medium positive then small negative	Small positive then small negative	Small positive then small negative	Medium positive then zero	Medium positive then small negative
Sr	Large positive then small negative	Small positive	Medium positive then small negative	Large then small positive	Medium then small positive	Erratic
TDS	Large positive then small negative	Medium positive then small negative	Medium positive then medium negative	Medium positive then small negative	Large positive then small positive and negative	Medium positive then small negative
Zn	Large positive then erratic positive and negative	Zero then large negative then small negative	Erratic large positive then large negative	Large positive then small negative	Large positive then large negative	Erratic large positive to large negative

NOTE: Large Positive = $A_L \geq 0.7$

Medium Positive = $0.04 < A_L < 0.7$

Small Positive = $0 < A_L \leq 0.04$

Small Negative = $-0.04 \leq A_L \leq 0$

Medium Negative = $0.7 < A_L < -0.04$

Large Negative = $A_L \leq -0.7$

TABLE 7-4. SUMMARY OF CONCENTRATION TRENDS WITH SUCCESSIVE REPETITIONS OF PROTOCOL STEP 6 ON EXXON PFBC WASTE

Element/ Species	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Al	Slight decrease	Increase	Variable, net increase	Net increase	Variable, no net change	Variable, no net change
B	Slight decrease	Net slight increase	Variable, net increase	Decrease	Variable, slight increase	Variable, net slight increase
Ba	Slight increase	Net constant	Constant	Net slight increase	Variable, no net change	Variable, no net change
Ca	Slight increase	Constant	Constant	Decrease	Decrease	Slight decrease
Cd	Constant	Net decrease	DL	DL	DL	DL
Cl	DL	Slight increase	DL	DL	DL	DL
Co	Slight decrease	Variable, net constant	DL	DL	DL	DL
Cr	Slight decrease	Variable, net constant	Variable, no net change	Slight decrease	Decrease to DL	Constant
Cu	Slight decrease	Increase	Net slight decrease	Slight decrease	Decrease to DL	Constant
F	Decrease	Variable	Variable, net slight increase	Decrease	Decrease	Decrease
Fe	Decrease	Increase	Net slight decrease	Variable, slight increase	Slight decrease	Decrease
K	Constant	Constant	Constant	Constant	Constant	Constant
Li	Decrease	DL	Increase	Variable, slight increase	Variable, no net change	DL
Mn	Increase	Increase	Increase	Variable, net increase	Increase	Slight increase
Mo	Decrease	Variable, net decrease	Decrease	Decrease	Decrease to DL	Constant

(continued)

TABLE 7-4. (Continued)

Element/ Species	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Na	Slight increase	Variable, slight increase	Constant	Slight increase	Slight increase	Increase
Ni	Slight decrease	Increase	Slight increase	DL	Slight increase	Constant
pH	Decrease	Decrease	Decrease	Decrease	Decrease	Decrease
Si	Increase	Increase	Net slight decrease	Increase	Increase	Increase
SO_4	Increase	Increase	Increase	Variable, no net change	Decrease	Variable, net increase
Sp.Cond.	Increase	Increase	Increase	Constant	Variable, slight decrease	Constant
Sr	Constant	Net increase	Slight decrease	Slight decrease	Slight decrease	Net decrease
TDS	Increase	Increase	Increase	Variable, net decrease	Variable, net decrease	Constant
Ti	Decrease	Variable, net increase	Variable, no net change	Slight decrease	Slight decrease	Net slight decrease
V	Decrease	Variable, net slight increase	Variable, no net change	DL	Slight increase	Net slight increase
Zn	Constant	Variable, net slight increase	Slight increase	Slight increase	Slight increase	DL

Note: DL = Detection Limit.

leachates from the lower sample point as a function of time of field cell operation; (2) computing the means, medians, and standard deviations of the concentrations for the leachates collected after 60 days of operation; and (3) calculating the field fractional attenuation (A_F) values using the mean concentrations (for the post 60-day period) for leachates collected from the upper and lower sample points of the cells. Details of the field cell attenuation results are given in Appendix E.

7.1.2.1 Concentration Trends During the Early Elution Period

Concentration trend plots were prepared using data from the initial (approximately 20 to 30 day) period of operation of the field cells. The plots were classed in the following trend categories: (1) increase; (2) moderate decrease; (3) large decrease; and (4) no appreciable change with time. The results of this categorization are shown in Table 7-5. Most of the parameters showed no appreciable change in concentration with time of field cell operation. Manganese and sodium showed moderate to large decreases for most cells except the alluvium-bearing cells, which showed an increase. Mg, SO_4, specific conductance, and TDS showed changes with time for most of the cells, but the direction of the trends was different for different cells. Cadmium was at the detection limit for all cells.

7.1.2.2 Average Concentrations During the Later Elution Period

Because the concentration trend plots showed considerable variation during the early elution period but smoothed out in the latter part of the period of operation, a second evaluation of the concentration trends was made using the data generated after 60 days of operation. The means and standard deviations of concentrations for each parameter in the post 60-day leachate are shown in Table 7-6. For all the field cells, the highest concentrations were noted for TDS, SO_4, Ca, K, Mg, and Na. Significant concentrations were also noted for chloride and silicon. The pH showed slightly basic conditions (7.3 to 7.6) for all field cells except the cell with the alluvium layer, which had a mean pH of 5.6.

TABLE 7-5. CONCENTRATION TRENDS FOR THE LOWER SAMPLING POINT OF THE EXXON PFBC FIELD CELLS (EARLY ELUTION PERIOD)

Element/ Species	Cell 1 Shale	Cell 2 Shale	Cell 3 Glacial Till	Cell 4 Limestone	Cell 5 Alluvium	Cell 6 Sandstone
Al	N	N	N	N	N	N
B	N	N	N	N	N	N
Ba	N	N	N	N	N	N
Ca	N	N	N	N	N	N
Cd	DL	DL	DL	DL	DL	DL
Cl	N	N	N	N	N	N
Co	N	N	N	N	N	D
Cr	N	N	N	N	N	N
Cu	M	M	N	N	N	M
F	N	N	N	N	N	N
Fe	N	N	N	N	N	M
Mg	N	N	I	M	I	M
Mn	M	M	M	M	I	D
Mo	N	M	N	N	N	N
Na	M	D	N	D	I	D
Ni	N	N	N	N	N	D
pH	N	N	N	N	N	N
Si	N	N	N	N	N	N
SO_4	N	N	I	D	I	M
Sp. Cond.	N	N	N	D	I	N
Sr	N	N	N	N	N	N
TDS	N	N	N	D	I	D
Ti	N	N	N	N	N	N
V	N	N	N	N	N	N
Zn	N	N	N	N	N	N

I = Increase with time.
M = Moderate decrease (from two to four times the initial values).
D = Large decrease (from five to ten times the initial values).
N = No appreciable change.
DL = Detection limit.

TABLE 7-6. MEAN AND STANDARD DEVIATION OF CONCENTRATIONS OF SEVERAL SPECIES IN LEACHATES FROM THE LOWER SAMPLE POINTS OF THE EXXON PFBC FIELD CELLS[1]

Element/ Species	Cell 1 Shale		Cell 2 Shale		Cell 3 Glacial Till		Cell 4 Limestone		Cell 5 Alluvium		Cell 6 Sandstone	
	$\bar{x}$[2]	σ[3]	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Al	1.6	0.8	1.7	0.8	1.7	1.0	1.5	0.8	1.5	0.8	2.8	1.4
B	3.0	2.4	3.5	2.1	3.3	1.9	3.9	2.0	3.0	2.0	3.8	2.7
Ba	0.2	0.2	0.2	0.3	0.3	0.3	0.2	0.3	0.2	0.3	0.2	0.3
Ca	550	24	550	60	500	110	475	46	344	100	500	50
Cd	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
Cl	20	12	29	50	17	10	7	7	14	11	16	6
Co	0.03	0.03	0.03	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03
Cr	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.07	0.05	0.06	0.06	0.07
Cu	0.02	0.03	0.02	0.03	0.02	0.03	0.02	0.04	0.04	0.05	0.04	0.05
F	0.22	0.05	0.20	0.06	0.48	0.35	1.19	0.24	0.23	0.08	0.34	0.12
Fe	0.04	0.04	0.07	0.06	0.04	0.04	0.08	0.20	0.05	0.05	0.05	0.04
K	290	90	330	140	50	40	270	150	230	140	390	110
Li	0.09	0.08	0.18	0.10	0.26	0.14	0.62	0.62	0.11	0.27	0.85	0.45
Mg	200	70	180	60	190	80	140	60	70	60	310	100
Mn	0.05	0.09	0.05	0.08	0.06	0.09	0.17	0.14	4.6	4.5	3.0	4.1
Mo	0.05	0.09	0.05	0.10	0.06	0.12	0.36	0.40	0.08	0.12	0.08	0.13
Na	180	50	110	40	160	130	190	200	190	230	110	60
Ni	0.04	0.05	0.04	0.04	0.04	0.04	0.13	0.08	0.13	0.09	0.09	0.07
pH[4]	7.4	0.3	7.4	0.2	7.4	0.2	7.6	0.3	5.6	0.3	7.3	0.2
Si	14.6	10.2	14.3	11.1	22.4	11.1	17.2	12.2	14.8	7.7	13.1	9.4
SO_4	2800	400	2500	500	2000	800	2600	1300	2100	1200	3100	700
Sp.Cond.[5]	4500	600	4300	1000	3300	900	4500	2500	3700	1600	4900	1100
Sr	1.5	0.3	1.4	0.3	0.4	0.2	7.5	0.9	0.8	0.3	1.7	0.3
TDS	4800	600	4400	900	3700	1300	4800	2300	3600	1800	5300	1100
Ti	0.11	0.20	0.10	0.15	0.12	0.22	0.16	0.26	0.15	0.26	0.18	0.26
TIC	54	9	59	13	59	6	58	16	1	0	56	3
TOC	8	3	11	4	19	10	8	2	5	2	4	1
V	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.2	0.3	0.4
Zn	0.2	0.3	0.2	0.3	0.2	0.3	0.3	0.4	0.3	0.5	0.4	0.5

[1] Units are mg/L unless otherwise noted

[2] $\bar{x}$ = mean

[3] σ = standard deviation

[4] Units are standard pH units

[5] Units are micromhos/cm

The concentrations of some of the parameters were significantly higher in leachates from the field cell with the upper layer of limestone than from the other cells. This was true for F, Li, Mo, and Sr. Chloride was lower in leachates from the limestone cell than in the other leachates. Higher concentrations of Al, Li, Mg, and Mn were observed in the leachates from the sandstone-bearing field cell than the other cells. Leachate from the alluvium-bearing cell was higher in manganese but lower in magnesium and TIC than the other cells. Potassium was lower in the till-bearing cell than in the others.

7.1.2.3 Fractional Attenuation During the Later Elution Period

In order to assess the long-term overall attenuation resulting from the layer of disposal media below the waste in the field cells, the field fractional attenuation (A_F) was determined using the post 60-day mean concentration values for the upper and lower sample points. This method of computing the fractional attenuation has the advantage that the lag-time in samples collected from the upper and lower points (see Appendix E) is smoothed over by using the long-term mean concentrations. Table 7-7 shows these long-term fractional attenuation values for each parameter and each field cell.

The species which experienced the highest positive attenuation for most of the field cells were Mo, Si, B, and Ca. The highest negative attenuation (i.e., mobilization) was shown by Mg, Al, Na, Ti, TIC, V, Zn, and SO_4. The majority of the other species showed attenuation rather than mobilization for most of the field cells. The field cell which showed attenuation for the most species was one of the shale-bearing cells, which showed attenuation for 13 of 20 species. The sandstone-bearing cell showed the greatest propensity for mobilization, with 14 of 20 species mobilized.

TABLE 7-7. AVERAGE FRACTIONAL ATTENUATION (A_F) FOR THE EXXON PFBC FIELD CELLS (After 60 days of operation)

Element/ Species	Cell 1 Shale	Cell 2 Shale	Cell 3 Glacial Till	Cell 4 Limestone	Cell 5 Alluvium	Cell 6 Sandstone
Al	−0.87	−0.68	−1.6	−1.5	−1.1	−1.8
B	0.31	0.34	0.32	0.08	0.11	0.05
Ba	0.24	−0.13	−0.044	0.21	0.11	0.13
Ca	−0.078	0.12	0.019	0.074	0.14	0.045
Cr	0.063	0.35	−0.054	−0.67	−0.51	−0.93
Cu	0.26	0.16	0.3	0.0035	−1.0	−2.1
Fe	0.69	0.14	0.48	−0.84	−0.13	0.49
K	0.18	0.3	0.83	−0.036	0.58	−0.57
Li	0.83	0.58	0.56	−0.54	0.91	−0.42
Mg	−2.7	−0.77	−3.2	−4.4	−2.2	−2.8
Mn	0.96	0.99	0.94	0.32	−13.1	−9.9
Mo	0.71	0.60	0.82	−1.2	0.56	0.53
Na	−0.68	0.39	−0.83	−1.5	−0.13	−0.63
Si	0.14	0.51	0.24	0.21	0.59	0.30
SO_4	−0.36	0.10	−0.064	−0.56	−0.048	−0.69
Sr	−0.23	−0.15	0.67	−3.8	0.38	−0.38
Ti	−0.40	−0.058	−0.23	−0.29	−0.14	−0.20
TIC	−0.42	−0.86	−3.4	−0.15	1	−0.22
V	−0.31	−0.11	−0.51	−1	−0.68	−0.67
Zn	−0.60	0.18	−0.53	−1.0	−1.3	−0.59

7.2 Attenuation of Alliance AFBC Waste Leachate

The attenuation of Alliance AFBC waste leachate was evaluated in the batch equilibration protocol and in five field cells. The attenuation of leachate in the laboratory leaching columns is described in Section 5.2.2.

7.2.1 Attenuation in the Batch Equilibration Protocol

7.2.1.1 Initial Attenuation: Protocol Step 4

Table 7-8 shows the Step 4 fractional attenuation values for Alliance AFBC waste and each of the disposal media. Exposure to shale resulted in mobilization of more parameters than were attenuated. Most strongly mobilized were Si, Cu, V, and B. Only lithium, barium, and calcium were substantially attenuated. For interburden, fluoride and silicon were most strongly mobilized. Fe, Zn, Mg, and Ba were the most attenuated parameters. Exposure to the sandstone resulted in the most substantial attenuation of Ba, Ni, and Fe. Si, F, K, Mo, and Na were weakly mobilized.

Glacial till provided the best attenuation for Zn, B, Ba, and Li, and contributed silicon the most. Cu, F, Mo, and Na were weakly mobilized. Attenuation by alluvium was greatest for Zn, Ni, Li, and B. Fluoride and iron were most strongly mobilized. For limestone, the parameters that were attenuated the most were Cr, Fe, Ni, Zn, and B. Fluoride, sodium, and silicon were the most mobilized parameters.

The parameters which were consistently attenuated by all disposal media were Ba, Ca, Cr, Li, SO_4, and TDS. Four parameters, F, Mo, Na, and Si, were consistently mobilized when the Alliance AFBC waste leachate was exposed to each of the six disposal media.

TABLE 7-8. SUMMARY OF STEP 4 LABORATORY FRACTIONAL ATTENUATION (A_L) VALUES FOR ALLIANCE AFBC WASTE LEACHATE AND FOR EACH DISPOSAL MEDIUM

Element/ Species	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Al	-0.18	0.62	0.82	0.47	0.74	0.77
B	-1.1	0.77	0.60	0.97	0.88	0.97
Ba	0.73	0.84	0.96	0.90	0.17	0.68
Ca	0.67	0.55	0.46	0.67	0.58	0.50
Cl	*	0.019	*	0.003	0.009	-0.057
Cr	0.38	0.72	0.43	0.72	0.54	1.00
Cu	-1.6	0.61	0.26	-0.68	*	0.69
F	*	-7.06	-0.44	-0.36	-4.6	-1.5
Fe	0.21	1.0	0.88	*	-1.8	1.0
K	-0.027	0.029	-0.32	0.44	0.15	-0.95
Li	0.81	0.90	0.77	0.86	0.97	0.43
Mo	-0.32	-0.29	-0.12	-0.58	-0.037	-0.34
Na	-0.34	-0.31	-0.24	-0.35	-0.03	-1.4
Ni	-0.39	1.00	0.89	1.00	1.00	1.0
Si	-3.5	-1.5	-0.73	-6.7	-1.7	-1.3
SO_4	0.54	0.45	0.34	0.47	0.56	0.44
Sr	0.31	0.26	0.064	0.48	0.17	-0.067
TDS	0.6	0.4	0.5	0.63	0.55	0.50
Ti	-0.85	0.52	0.36	0.66	0.65	0.63
V	-1.4	0.40	*	0.47	0.54	0.48
Zn	-0.52	1.0	0.75	1.0	1.0	1.0

NOTE: Each value is a mean of duplicate pairs. Dash indicates initial (Step 1) concentration value was at the detection limit.

* = One value was positive and one was negative, so no mean value is reported.

7.2.1.2 Repeated Exposure of Disposal Media to Fresh Leachate: Protocol Step 5

Table 7-9 shows the trends in fractional attenuation with increasing volume-per-mass ratio (repetitions of Step 5) for the Alliance AFBC waste. As was the case for the Exxon PFBC waste, the attenuation behavior was highly variable, both for the different species and the various disposal media. Calcium, sulfate, and TDS again showed generally decreasing attenuation with Step 5 repetition, but other species varied in their behavior for the different media. The dominant trend observed was little or no trend at all (i.e., erratic behavior). Glacial till exhibited dominantly decreasing attenuation with increasing volume-per-mass ratio, but the other media showed no consistent attenuation trends for the various chemical species.

7.2.1.3 Repeated Exposure of Leachate Samples to Fresh Disposal Media: Protocol Step 6

Table 7-10 shows the fractional attenuation trends for various species of interest in the Alliance AFBC waste leachate during repetitions of protocol Step 6. Most species showed erratic behavior or different behavior when exposed to different types of disposal media. Calcium, however, showed decreasing attenuation from medium positive values to zero or small negative values. Silicon exhibited consistently negative fractional attenuation. Sulfate and TDS, like calcium, showed declining values, generally from medium or small positive to small negative.

Table 7-11 shows the concentration trends for several parameters resulting from repetitions of Step 6. The parameters which showed a decreasing concentration trend for most of the disposal media were Mo, pH, and Sr. The parameters showing an increase were Mn, Na, Si, SO_4, and Zn. Potassium remained constant, and other parameters behaved differently for different disposal media. None of the disposal media had a consistent effect on all of the parameters.

TABLE 7-9. TRENDS OF LABORATORY FRACTIONAL ATTENUATION (A_L) WITH SUCCESSFUL REPETITIONS OF PROTOCOL STEP 5 ON ALLIANCE AFBC WASTE

Element/ Species	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Al	Erratic	Erratic decrease	Decreasing to erratic negative	Decreasing to erratic negative	Erratic increase	Erratic decrease
B	Erratic increase to positive	Decrease to erratic negative	Decrease to erratic negative	Decrease to erratic negative	Erratic decrease	Erratic decrease
Ba	Decrease to erratic negative	Erratic decrease	Decrease then erratic increase	Decreasing to erratic negative	Decreasing to erratic negative	Erratic decrease
Ca	Erratic decrease	Erratic decrease	Erratic decrease	Erratic decrease	Erratic decrease	Erratic decrease
Cr	Erratic	Erratic decrease	Erratic	Decrease to	Decrease to	Decrease to
F	Decrease to erratic negative	Increase to zero	Erratic positive	Erratic negative	Increasing negative	Erratic negative
Fe	Erratic	Erratic positive	Decrease to erratic negative	Erratic	Erratic negative	Decrease to erratic negative
Na	Increasing negative	Increase to erratic positive	Increase to positive	Increase to positive	Decrease then increase	Decrease then increasing negative
Si	Increase to positive	Increase to positive	Erratic positive and negative	Increase to positive	Increase to positive	Increasing negative
SO_4	Consistent decrease	Erratic decrease	Decrease	Consistent decrease	Increase then decreasing positive	Decrease to erratic negative
Sr	Erratic	Decrease to erratic negative	Decrease then erratic increase	Erratic decrease	Decrease then erratic increase	Increase to positive
TDS	Consistent increase	Decrease then increase	Decrease	Consistent decrease	Decrease	Consistent decrease
Zn	Increase to erratic positive	Constant	Decrease to erratic negative	Erratic decrease	Decrease to erratic negative	Decrease then increase

TABLE 7-10. TRENDS OF LABORATORY FRACTIONAL ATTENUATION (A_L) WITH SUCCESSIVE REPETITIONS OF PROTOCOL STEP 6 ON ALLIANCE AFBC WASTE

Element/ Species	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Al	Erratic	Erratic large negative	Large positive then medium negative	Erratic large positive then large negative	Erratic	Erratic large positive then large negative
B	Large negative then small positive	Erratic medium positive then medium negative	Medium positive then medium negative	Erratic large positive	Erratic large positive	Large positive then large negative
Ba	Large positive then large negative	Erratic medium negative and large positive	Large positive then erratic large negative	Positive then erratic negative	Negative then positive	—
Ca	Medium positive then small negative	Medium positive then small negative	Medium positive then small negative	Medium positive decreasing to zero	Medium positive decreasing to zero	Medium positive decreasing to zero
Cr	Erratic positive and negative	Erratic	Medium positive then erratic medium negative	Large positive then small negative	Erratic large positive	Large positive decreasing to small positive
Fe	Erratic	Erratic, zero to large negative	Large positive then erratic negative	Erratic	Erratic	Erratic; large positive then medium negative
Na	Small negative then small positive	Small negative	Small negative increasing to zero	?	Negative	Large negative increasing to small negative
Si	Large then small negative	Large then small negative	Erratic negative	Small negative increasing to zero	Erratic negative	Erratic negative
SO_4	Medium positive then small negative	Small positive then small negative	Small positive then small negative	Medium positive then small negative	Medium positive decreasing to zero	Medium positive then small positive and
Sr	Small positive	Medium then small positive	Small positive	Small positive increasing to medium positive	Small positive	Small negative then medium positive
TDS	Medium positive then small negative	Medium positive then small negative	Medium positive then medium negative	Medium positive then small negative	Medium positive them small negative	Medium positive then small negative
Zn	Medium negative then small positive	Erratic	Medium positive then medium negative	Large positive then small negative	Erratic large positive to large negative	Erratic large positive to large negative

NOTE: Large positive = $A_L \geq 0.7$

Medium positive = $0.04 < A_L < 0.07$

Small positive = $0 < A_L \leq 0.04$

Small negative = $-0.04 \leq A_L \leq 0$

Medium negative = $-0.7 < A_L < -0.04$

Large negative = $A_L \leq -0.7$

TABLE 7-11. SUMMARY OF CONCENTRATION TRENDS WITH SUCCESSIVE REPETITIONS OF PROTOCOL STEP 6 ON ALLIANCE AFBC WASTE

Element/ Species	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Al	Variable, no net change	Increase	Increase	Slight increase	Variable, no net change	Variable, no net change
B	Variable, no net change	Net decrease	Increase	Decrease to DL	Variable, no net change	Variable, net slight increase
Ba	Variable	Decrease	Variable	Variable, no net change	Variable, net decrease	Variable, no net change
Ca	Increase	Slight increase	Increase	Decrease	Decrease	Decrease
Cd	Slight decrease	Increase	Slight increase	DL	DL	DL
Cl	Variable	Variable increase	Variable	Decrease	Constant	Increase
Co	Variable, slight increase	Increase	Slight increase	Decrease to DL	Slight increase	DL
Cr	Variable, slight increase	Variable, net decrease	Slight increase	Slight decrease	Slight decrease	Decrease to DL
Cu	Variable, slight increase	Increase	Net slight increase	Slight decrease	Slight decrease	DL
F	Slight decrease	Variable, no net change	Net slight increase	Decrease	Variable, no net change	Increase
Fe	Variable, slight increase	Increase	Variable, net slight increase	Slight decrease	Variable, slight decrease	Constant
K	Constant	Constant	Constant	Constant	Constant	Constant
Li	Decrease	Increase	Slight increase	Decrease	Variable, slight decrease	Constant
Mn	Increase	Increase	Increase	Increase	Increase	Variable around DL
Mo	Decrease	Decrease	Decrease	Decrease	Decrease to zero	Increase

(continued)

TABLE 7-11. (Continued)

Element/ Species	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Na	Increase	Increase	Increase	Increase	Increase	Constant
Ni	Variable, slight increase	Increase	Slight increase	Variable, slight decrease	Slight increase	Slight decrease
pH	Decrease	Decrease	Decrease	Decrease	Decrease	Decrease
Si	Increase	Increase	Variable, net increase	Increase	Increase	Variable, slight increase
SO_4	Increase	Increase	Increase	Variable, slight increase	Variable, net slight decrease	Constant
Sp.Cond.	Slight increase	Increase	Increase	Constant	Constant	Variable, slight decrease
Sr	Decrease	Decrease	Decrease	Decrease	Decrease	Decrease
TDS	Increase	Increase	Increase	Increase	Variable decrease	Variable, slight increase
Ti	Variable, net slight increase	Variable, net increase	Slight increase	Slight decrease	Variable, slight decrease	DL
V	Variable, net slight increase	Varible, net increase	Net slight increase	Slight decrease	Variable, net slight decrease	Slight decrease to DL
Zn	Variable, net slight increase	Increase	Slight increase	Slight increase	Slight increase	Variable around DL

Note: DL = Detection Limit.

7.2.2 Attenuation in the Field Cells

As for the Exxon PFBC field cells, the attenuation data from the Alliance AFBC field cells were evaluated in three ways: (1) by preparing plots of concentration of leachates from the lower sample point as a function of time of field cell operation; (2) by computing the means, medians, and standard deviations of the concentrations of the leachates collected after 60 days of operation; and (3) by calculating the field fractional attenuation (A_F) values using the mean concentrations for the post 60-day period for leachates collected from the upper and lower sample points of the cells.

7.2.2.1 Concentration Trends During the Early Elution Period

Table 7-12 presents a summary of the concentration trends during the initial period of operation of the Alliance AFBC field cells. Most of the parameters showed a trend of no appreciable change. Only magnesium showed consistent behavior, with decreasing trends for all field cells. Calcium and chloride showed different trends for different field cells. Cadmium and cobalt were below the detection limits in leachates from most of the field cells. Calcium, one of the few parameters to shown an increase, did so in the cells containing alluvium.

7.2.2.2 Average Concentrations During the Later Elution Period

Table 7-13 shows the means and standard deviations of concentrations in leachates collected from the Alliance field cells after 60 days of operation. The cell containing interburden showed very acid conditions (mean pH of 2.1) and higher concentrations of more (17 of 29) parameters than the other cells, which is not surprising since it is analogous to an acid mine drainage system. Of the remaining four cells, the limestone cell contained substantially higher levels of K, Li, Mo, Na, and Sr than the others. The two alluvium-bearing cells showed consistently lower concentrations of potassium and magnesium. The alluvium cells had slightly acid conditions (pH of 5.5 to 6.3), and the limestone and shale cells were slightly basic. The shale-bearing cell had elevated concentrations of aluminum and calcium.

TABLE 7-12. CONCENTRATION TRENDS IN LEACHATES FROM THE LOWER SAMPLING POINT OF THE ALLIANCE AFBC FIELD CELLS (EARLY ELUTION PERIOD)

Element/ Species	Cell 13 Interburden	Cell 14 Alluvium	Cell 15 Alluvium	Cell 16 Limestone	Cell 17 Shale
Al	D	–	N	N	N
B	N	–	N	M	N
Ba	N	–	N	N	N
Ca	N	I	I	M	N
Cd	D	DL	DL	DL	DL
Cl	D	N	I	D	M
Co	N	DL	DL	DL	DL
Cr	N	N	N	D	N
Cu	N	N	N	N	N
F	N	N	N	N	N
Fe	D	N	N	N	N
K	N	–	N	N	N
Li	N	–	D	N	N
Mg	D	–	D	D	D
Mn	N	–	N	I	N
Mo	N	–	N	N	N
Na	–	–	N	N	I
Ni	N	N	N	N	N
pH	N	N	N	N	N
Si	I	N	N	N	N
SO_4	D	–	N	N	N
Sp.Cond.	D	I	N	N	N
Sr	N	N	N	N	N
TDS	D	–	I	N	N
Ti	N	–	N	N	N
V	N	N	N	N	N
Zn	N	N	N	N	N

I = Increase with time.
M = Moderate decrease (from two to four times the initial values).
D = Large decrease (from five to ten times the initial values).
N = No appreciable change.
DL = Detection limit.

TABLE 7-13. MEAN AND STANDARD DEVIATION OF CONCENTRATIONS OF SEVERAL SPECIES IN LEACHATES FROM THE LOWER SAMPLE POINTS OF THE ALLIANCE AFBC FIELD CELLS[1]

Element/ Species	Cell 13 Interburden $\bar{x}$[2]	Cell 13 Interburden σ[3]	Cell 14 Alluvium $\bar{x}$	Cell 14 Alluvium σ	Cell 15 Alluvium $\bar{x}$	Cell 15 Alluvium σ	Cell 16 Limestone $\bar{x}$	Cell 16 Limestone σ	Cell 17 Shale $\bar{x}$	Cell 17 Shale σ
Al	520	350	4.0	11	2.5	6.5	5.6	14	10	28
B	38	110	8.3	26	9.7	32	13	37	13	37
Ba	0.2	0.3	0.5	0.4	0.6	0.4	0.4	0.4	0.3	0.3
Ca	520	56	240	57	200	24	390	135	680	85
Cd	0.30	0.34	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
Cl	38	33	320	230	350	53	99	42	140	140
Co	4.0	3.4	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03
Cr	0.30	0.40	0.02	0.01	0.01	0.03	0.02	0.04	0.04	0.06
Cu	8.0	7.0	0.01	0.01	0	0	0.02	0.03	0.03	0.06
F	3.5	1.5	0.15	0.16	0.12	0.12	1.31	0.18	0.16	0.08
Fe	1050	610	0.72	0.80	0.07	0.06	0.05	0.06	0.18	0.32
K	110	54	10	3	9	2	320	140	65	29
Li	3.6	1.8	0	0.01	0	0	2.0	0.34	0.04	0.05
Mg	310	240	60	20	50	10	140	50	240	70
Mn	8.8	6.9	1.0	0.47	1.2	0.47	0.18	0.19	0.25	0.43
Mo	0.2	0.16	0	0.01	0	0	1.0	0.21	0.02	0.04
Na	50	20	90	40	50	20	240	100	100	40
Ni	9.1	7.52	0.05	0.04	0.05	0.03	0.06	0.06	0.05	0.05
pH[4]	2.1	0.1	5.5	0.6	6.3	0.3	7.5	0.2	7.4	0.2
Si	98	31	9.8	1.3	9.5	1.8	20	4.0	9.9	3.6
SO_4	9420	5880	430	280	220	150	1860	470	2070	230
Sp.Cond.[5]	7600	2100	1800	400	1500	100	3700	700	3600	300
Sr	7.5	3.7	0.9	0.4	0.8	0.1	11.5	3.2	3.8	5.5
TDS	13200	7300	1700	400	1400	200	3700	1000	4000	400
Ti	0	0	0.01	0.01	0.01	0	0.05	0.07	0.05	0.13
TIC	1	0	1	0	1	0	55	9	60	16
TOC	–	–	10	–	6	–	41	–	18	–
V	0.3	0.3	0.01	0.02	0.02	0.03	0.04	0.07	0.06	0.12
Zn	17	15	0.1	0	0.1	0.1	0.09	0.05	0.08	0.04

[1] Concentrations in mg/L unless otherwise noted

[2] $\bar{x}$ = mean

[3] σ = standard deviation

[4] Units are standard pH units

[5] Units are micromhos/cm

7.2.2.3 Fractional Attenuation During the Later Elution Period

The fractional attenuation values as determined using mean concentration data from the period of operation after 60 days are shown in Table 7-14 for the various species. Potassium and strontium were attenuated in all of the field cells, and molybdenum and silicon were attenuated in four of the five cells. The parameters which were mobilized in all the cells were Al, B, Mg, Ni, and Zn. Magnesium showed overall the strongest mobilization. Ba, Ca, Fe, and Mn were mobilized in four of the five cells.

The two alluvium field cells showed attenuation for the most parameters (13 to 15 of 21 were attenuated). The other three cells showed mobilization for more parameters than were attenuated, with four to eight parameters attenuated.

7.3 Attenuation of Georgetown AFBC Waste Leachate

The attenuation characteristics of the Georgetown AFBC waste leachate were measured in Step 4 of the laboratory batch equilibration protocol. Table 7-15 shows the fractional attenuation values derived from concentration data resulting performance of Step 4. Exposure to shale resulted in the most attenuation for TIC, Li, and Mg. Silicon was most strongly mobilized. For the interburden only TIC was substantially attenuated. Fluoride was the parameter most strongly mobilized. Sandstone attenuated nickel the most and contributed F, K, Na, and TOC weakly.

Glacial till attenuated TIC and Li the most; TOC, F, and Si were the parameters with the greatest mobilization. Alluvium showed the best attenuation for Ni, TIC, and Mg and the most mobilization for TOC and F. Only TIC was substantially attenuated by limestone, but F, Na, and K were all strongly mobilized.

The parameters which were most consistently attenuated by the various disposal media were Ba, Ca, Li, Mg, SO_4, specific conductance, Sr, TDS, and TIC. The parameters which were consistently mobilized were F, Na, and TOC.

TABLE 7-14. AVERAGE FRACTIONAL ATTENUATION (A_F) FOR THE ALLIANCE AFBC FIELD CELLS (After 60 days of Operation)

Element/ Species	Cell 13 Interburden	Cell 14 Alluvium	Cell 15 Alluvium	Cell 16 Limestone	Cell 17 Shale
Al	-2970	-7.4	-4.5	-17	-35
B	-5.6	-8.3	-12	-0.25	-0.18
Ba	0.33	-0.45	-0.29	-0.40	0.18
Ca	-1	-0.39	0.23	-0.19	-0.63
Cr	-28	0.81	0.62	-0.45	-0.97
Cu	-	0.36	1	-1	-1.1
Fe	-5070	-0.57	0.11	-1.7	-2.6
K	0.72	0.97	0.98	0.27	0.82
Li	-1	1	1	-0.13	0.97
Mg	-270	-120	-13	-400	-260
Mn	-87	-57	-35	0.36	-0.67
Mo	0.75	1	1	-0.058	0.98
Na	0.59	0.53	0.8	-1	-0.14
Ni	-1490	-0.18	-23	-2.6	-1.6
Si	-2.7	0.81	0.82	0.18	0.42
SO_4	-5.8	0.68	0.87	-0.60	-0.85
Sr	0.64	0.97	0.89	0.57	0.86
Ti	-	1	-	-21	-1.5
TIC	1	-	-	-0.38	-0.54
V	-16	0.95	0.86	-0.14	-0.79
Zn	-950	-	-	-3.6	-3.7

TABLE 7-15. SUMMARY OF STEP 4 LABORATORY FRACTIONAL ATTENUATION (A_L) VALUES FOR GEORGETOWN AFBC WASTE LEACHATE AND FOR EACH DISPOSAL MEDIUM

Element/ Species	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Ba	0.24	0.37	0.26	0.32	0.18	0.42
Ca	0.60	0.65	0.54	0.61	0.54	0.47
Cl	0.59	0.52	0.73	0.74	0.77	0.65
F	-0.18	-1	-0.59	-1.9	-0.70	-3.07
K	0.03	0.03	-0.28	0.57	0.31	-1.1
Li	0.99	0.62	0.91	0.87	1	0.51
Mg	0.82	0.53	*	0.22	0.88	0.67
Na	-0.31	-0.58	-0.32	-0.51	-0.015	-2.4
Ni	-0.15	1	1.00	-0.31	1	0.36
Si	-3.3	-0.18	0.091	-1.8	-0.18	0.12
SO_4	0.32	0.17	0.16	0.24	0.36	0.29
Sp. Cond.	0.68	0.56	0.48	0.67	0.57	0.45
Sr	0.34	0.29	0.19	0.54	0.31	0.077
TDS	0.64	0.41	0.58	0.51	0.62	0.56
TIC	1	1	0.83	1	1	1
TOC	-1.2	-0.70	-0.35	-2.0	-0.99	-0.54

NOTE: Each value is a mean of duplicate pairs.

* One value was positive and one was negative, so no mean value is not reported.

7.4 Comparison of the Attenuation of Leachates from the Three FBC Wastes

A comparison of the attenuation of leachates from the three FBC wastes when exposed to the six disposal media was made using the fractional attenuation values derived from analysis of the Step 4 data and the field cell data generated during the latter part of the operational period (after 60 days of operation). The fractional attenuation values were classed in five categories (strongly attenuated, weakly attenuated, not attenuated or mobilized, weakly mobilized, and strongly mobilized), and the results were tabulated for several parameters of interest as shown in Table 7-16.

Calcium was generally weakly attenuated by all of the disposal media in the lab studies but was not attenuated in the field cells. The field cell containing interburden showed strong mobilization of calcium. Sulfate showed a similar pattern of weak attenuation in the lab, but showed more mobilization than attenuation in the field cells. The behaviors of calcium and sulfate were quite consistent for leachates derived from the three different FBC wastes.

Potassium showed no effect or weak attenuation when the leachates were exposed to shale, interburden, glacial till, and alluvium in both the lab protocol and the field cells. It was weakly mobilized from the sandstone in the lab and field, but showed differing behavior in the lab and field when exposed to the limestone (strongly mobilized in the lab and no effect or weakly attenuated in the field). Sodium showed weak to strong mobilization in most components of the study, except that the Exxon PFBC leachate showed strong lab attenuation for the sandstone, glacial till, and alluvium media.

Magnesium showed mostly weak to strong attenuation; except for the Alliance AFBC leachates in the field cells, where strong mobilization occurred. Strontium was primarily weakly attenuated or not affected by the disposal media. Barium was generally weakly attenuated by four of the disposal media (shale, interburden, sandstone, and glacial till). It was not affected or weakly mobilized by the alluvium and showed mixed weak attenuation and mobilization by limestone. Lithium was mostly weakly to strongly

TABLE 7-16. COMPARISON OF THE ATTENUATION OF LEACHATES FROM THREE FBC WASTES RESULTING FROM EXPOSURE TO THE DISPOSAL MEDIA[1]

Element/ Species		Shale		Interburden		Sandstone		Glacial Till		Alluvium		Limestone	
		Lab[2]	Field[3]	Lab	Field	Lab	Field	Lab	Field	Lab	Field	Lab	Field
Al	EP[4]	SA	WM	WA	#	*[9]	SM	WM	SM	WM	SM	SM	SM
	AA[5]	N	SM	WA	SM	WA	#	WA	#	WA	SM	WA	SM
	GA[6]	–[7]	#[8]	–	#	–	#	–	#	–	#	–	#
B	EP	SA	WA	SA	#	SA	N	SA	WA	SA	N	SA	N
	AA	SM	N	WA	SM	WA	#	SA	#	WA/SA	SM	SA	SM
	GA	–	#	–	#	–	#	–	#	–	#	–	#
Ba	EP	*	WA	WA	#	*	N	*	N	WM	N	WM	WA
	AA	WA	N	WA	WA	SA	#	WA/SA	#	N	WM	WA	WM
	GA	WA	#	WA	#	WA	#	WA	#	N	#	WA	#
Ca	EP	WA	N	WA	#	WA	N	WA	N	WA	N	WA	N
	AA	WA	WM	WA	SM	WA	#	WA	#	WA	**[10]	WA	N
	GA	WA	#	WA	#	WA	#	WA	#	WA	#	WA	#
Cl	EP	–	–	SM	#	–	–	–	–	–	–	–	–
	AA	*	–	N	–	*	#	N	#	N	–	N	–
	GA	WA	#	WA	#	WA	#	WA	#	WA	#	WA	#
Cr	EP	SA	N/WA	*	#	WA	SM	WM	N	WM	WM	WM	WM
	AA	WA	SM	WA	SM	WA	#	WA	#	WA	WA	SA	WM
	GA	–	#	–	#	–	#	–	#	–	W	–	#
F	EP	WA	–	WM	#	WA	–	WA	–	WA	–	N	–
	AA	*	–	SM	–	WM	#	WM	#	SM	–	SM	–
	GA	EM/SM	#	SM	#	WM	#	SM	#	WM	#	SM	#
Fe	EP	*	N/WA	WA	#	WA	WA	WA	WA	SM	N	WA	WM
	AA	WA	SM	SA	SM	WA/SA	#	*	#	SM	N/WM	SA	SM
	GA	–	#	–	#	–	#	–	#	–	#	–	#
K	EP	N	N/WA	–	#	–	M	–	WA	–	WA	–	N
	AA	N	WA	N	WA	WM	#	WA	#	N	SA	SM	WA
	GA	N	#	N	#	WM	#	WA	#	WA	#	SM	#
Li	EP	SA	WA	SA	#	SA	WM	SA	WA	WA	WA/SA	WA	WM
	AA	WA	SA	WA/SA	SM	WA	#	WA	#	SA	SA	WA	N
	GA	SA	#	WA	#	SA	#	WA/SA	#	SA	#	WA	#
Mg	EP	SA	WM/SM	SA	#	SA	SA	SA	SA	SA	SA	SA	SA
	AA	–	SM	–	SM	–	#	–	#	–	SM	–	SM
	GA	WA	#	WA	#	*	#	WA	#	WA/SA	#	WA	#
Na	EP	–	**	WM	#	SA	WM	SA	WM	SA	N	WA	SM
	AA	WM	N	WM	WA	WM	#	WM	#	N	WA	SM	SM
	GA	WM	#	WM	#	WM	#	WM	#	N	#	SM	#

(continued)

TABLE 7-16. (Continued)

Element/ Species		Shale		Interburden		Sandstone		Glacial Till		Alluvium		Limestone	
		Lab[2]	Field[3]	Lab	Field	Lab	Field	Lab	Field	Lab	Field	Lab	Field
Ni	EP	–	–	SA	#	–	–	SM	–	SA	–	SM	–
	AA	WM	SM	SA	SM	WA	#	SA	#	SA	WM/SM	SA	SM
	GA	N	#	SA	#	SA	#	WM	#	SA	#	WA	#
Si	EP	*	N/WA	WA	#	WA	WA	WM	WA	WM	WA	WM	WA
	AA	SM	WA	SM	SM	SM	#	SM	#	SM	WA	SM	N
	GA	SM	#	N	#	N	#	SM	#	N	#	N	#
SO	EP	WA	N/WM	NA	#	WA	WM	WA	N	WA	N	WA	WM
	AA	WA	WM	WA	SM	WA	#	WA	#	WA	WA	WA	WM
	GA	WA	#	NA	#	NA	#	WA	#	WA	#	WA	#
Sr	EP	WA	N/WM	*	#	N	WM	WA	WA	WA	WA	N	SM
	AA	WA	WA	WA	WA	N	#	WA	#	N	WA	N	WA
	GA	WA	#	WA	#	WA/SA	#	WA	#	WA	#	N	#
TDS	EP	WA	–	WA	#	WA	–	WA	–	WA	–	WA	–
	AA	WA	–	WA	–	WA	#	WA	#	WA	–	WA	–
	GA	WA	#	WA	#	WA	#	WA	#	WA	#	WA	#
Zn	EP	*	NA/WM	*	#	SA	WM	SA	WM	SA	SM	WA	SM
	AA	WM	SM	SA	SM	WA	#	SA	#	SA	–	SA	SM
	GA	–	#	–	#	–	#	–	#	–	#	–	#

[1]SA = Strong Attenuation ($A \geq 0.9$)
WA = Weak Attenuation ($0.2 < A \leq 0.9$)
N = No Attenuation or Mobilization ($-0.2 < A \leq 0.2$)
WM = Weak Mobilization ($-0.9 < A \leq -0.2$)
SM = Strong Mobilization ($A \leq -0.9$).

[2]Lab Protocol Step 4.

[3]Field Cell Lower Sample Point, Last Few Months of Operation.

[4]EP = Exxon PFBC.
[5]AA = Alliance AFBC.
[6]GA = Georgetown AFBC.
[7](–) = Step 1 concentration was at detection limit.
[8](*) = One value of duplicate pairs was negative and one was positive, so no mean value is reported.
[9](#) = No field cell.
[10]*** = Different results from duplicate field cells.

attenuated in the lab and field cell studies, with the exception of the field cell containing interburden.

Silicon was mostly mobilized in the field studies and mostly attenuated in the lab studies. Except for the alluvium, the disposal media attenuated iron in the lab studies; the results for the field cells were different for different media. Barium was attenuated in the lab and field studies including shale, interburden, sandstone, and till. Barium was mobilized from alluvium and showed mixed behavior in the studies involving limestone. Boron showed mostly different behavior for the different waste leachates and disposal media. The trace elements chromium and zinc also showed variable behavior.

8.0 OVERALL ASSESSMENT OF THE SUITABILITY OF FBC WASTES FOR LAND DISPOSAL

An overall assessment of the acceptability of the FBC wastes for land disposal was performed by comparing: (1) the bulk composition of FBC wastes with that of the disposal media; (2) the quality of FBC waste leachate with similar leachate derived from the disposal media; and (3) the concentrations of various parameters found in FBC waste leachate with accepted water quality standards and criteria.

8.1 Comparison of FBC Waste Composition with Disposal Media Composition

The solids composition of the three FBC wastes and the six disposal media were tabulated together (Table 8-1) to allow a direct comparison to be made among them. For most parameters, the compositions of the wastes and disposal media were quite comparable. With the exception of limestone, the media had a generally higher aluminum content than the FBC wastes. The wastes had a higher calcium content than all the media except limestone, which had about the same calcium content as the wastes. The intermediate calcium content of the glacial till reflects its "high lime" composition (see Appendix A). The iron content of the wastes and five of the disposal media was very comparable; limestone was again the exception, with an iron content an order of magnitude below the wastes and the other disposal media.

The potassium content of the Exxon PFBC waste was similar to that of five of the media. The Alliance and Georgetown wastes had lower potassium values more comparable to the limestone media. Because of the dolomite sorbent used, the Exxon PFBC waste had a substantially higher magnesium content than any of the other wastes and disposal media. The limestone and glacial till, which had higher calcium values, also had higher magnesium values.

TABLE 8-1. BULK SOLIDS COMPOSITION OF THE FBC WASTES AND DISPOSAL MEDIA

Element/ Species		Exxon PFBC	Alliance AFBC	Georgetown AFBC	Shale	Interburden	Sandstone	Glacial Till	Alluvium	Limestone
Al	(g/100g)	2.4	2.0	2.9	9.4	9.9	9.5	6.2	4.1	1.5
Ca	"	22	31	32	1.1	0.53	0.38	5.7	0.14	32
Fe	"	3.0	5.3	2.8	4.2	2.3	4.3	3.4	3.0	0.72
K	"	2.2	0.42	0.50	2.7	1.7	3.0	2.4	1.2	0.75
Mg	"	12	0.47	0.46	0.85	0.4	0.74	1.7	0.30	1.1
Si	"	5.2	4.2	5.8	24	19	26	23	35	4.1
SO_4	"	23	13	0.46	0.36	0.64	0.53	<0.10	<0.10	0.12
Ag	(mg/kg)	<0.25	<0.25	6.2	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25
B	"	190	<2.25	390	130	130	130	74	60	47
Ba	"	87	290	160	500	960	530	300	150	60
Be	"	8.6	4.8	14	7.5	5.8	8.7	5.9	5.1	1.8
Cd	"	0.44	0.17	—	0.13	0.19	0.11	0.15	0.11	0.13
Cl	"	280	840	370	<40	<40	54	48	<40	120
Co	"	13	9.0	9.2	20	<15	<15	15	<15	<15
Cr	"	130	32	73	80	100	78	65	52	50
Cu	"	59	38	27	37	51	40	44	30	28
Li	"	<2.5	<2.5	39	55	130	68	20	40	<2.5
Mn	"	130	600	290	750	3300	520	530	620	180
Mo	"	26	27	7.4	<2.4	<2.4	<2.4	14	<2.4	<2.4
Na	"	5200	<13.3	1400	3100	6900	3000	4600	3700	1290
Ni	"	56	41	16	48	60	43	48	21	15
Sr	"	160	820	260	170	180	110	130	70	370
Ti	"	1590	1500	1800	5500	5400	4700	3660	3900	1080
V	"	130	17	51	130	150	140	140	92	89
Zn	"	290	68	34	94	90	92	87	51	32

The silicon contents of the five disposal media besides limestone were quite similar and were generally four to six times higher than in the waste. The limestone had a comparable silicon value to the waste. With respect to sulfate, the Exxon PFBC and Alliance AFBC wastes were much higher (almost two orders of magnitude) than the disposal media. The Georgetown AFBC sulfate content was anomalously low and was comparable to the media.

Most of the rest of the parameters were similar in concentration for the wastes and disposal media. The parameters whose concentrations were thus similar were B (except Alliance AFBC waste, which was much lower), Ba, Be, Cd, Co, Cr, Cu, Mn, Na (except Alliance waste), Ni, Sr (except Alliance), V (except Alliance), and Zn (except Exxon waste). The wastes had generally higher chloride contents than the disposal media. Lithium in the Georgetown waste was comparable to five of the disposal media. Lithium was lower in the Exxon and Alliance waste and was more comparable to the limestone medium lithium values. Molybdenum was higher in the wastes than in all the media except the till. Titanium was higher in all the media (except limestone) than in the waste.

In general, the FBC wastes contained about the same amount of the minor and trace elements as the disposal media. The wastes contained more Ca, Mg (Exxon PFBC waste only), SO_4 (except Georgetown AFBC waste), Cl, and Mo. The media were generally higher than the wastes in Al, K, and Si content.

8.2 Comparison of FBC Waste Leachate With Disposal Media Leachate

A detailed comparison of the leachates from Steps 1, 2, and 3 of the laboratory protocol, from the upper sample point of the waste-bearing field cells, from the laboratory leaching columns, and from lab and field leaching of the disposal media is given in Appendix I (Section I.6). For each parameter, the concentration ranges (or means) observed in each of the leachate generation components of the project are plotted on the same diagram so that a direct comparison of the concentrations can be easily made. Table 8-2 presents a summary of visual comparison that were made from the concentration diagrams in Appendix I. It is recognized that the experimental

TABLE 8-2. GENERAL COMPARISON OF WASTE LEACHATE WITH DISPOSAL MEDIA LEACHATE CONCENTRATIONS

Element/ Species	Waste	Waste Leachate Compared to Media Leachate[1] Lab[2]	Field[3]
Al	Exxon PFBC	Somewhat higher	Somewhat lower
	Alliance AFBC	Somewhat higher	Somewhat lower
	Georgetown AFBC	Somewhat lower	Somewhat lower
B	Exxon PFBC	Higher	Somewhat higher
	Alliance AFBC	Higher	Similar
	Georgetown AFBC	Somewhat higher	—
Ba	Exxon PFBC	Somewhat higher	Similar
	Alliance AFBC	Similar	Similar
	Georgetown AFBC	Somewhat higher	—
Ca	Exxon PFBC	Higher	Mixed
	Alliance AFBC	Higher	Mixed
	Georgetown AFBC	Higher	—
Cd	Exxon PFBC	Detection limit	Detection limit
	Alliance AFBC	Detection limit	Detection limit
	Georgetown AFBC	Detection limit	—
Cl	Exxon PFBC	Similar	Somewhat higher
	Alliance AFBC	Higher[4]	Higher
	Georgetown AFBC	Similar	—
Co	Exxon PFBC	Similar	Detection limit
	Alliance AFBC	Similar	Detection Limit
	Georgetown AFBC	Detection limit	—
Cr	Exxon PFBC	Similar	Similar
	Alliance AFBC	Similar	Similar
	Georgetown AFBC	Similar	—
Cu	Exxon PFBC	Somewhat higher	Similar
	Alliance AFBC	Somewhat higher	Similar
	Georgetown AFBC	Somewhat higher	—
F	Exxon PFBC	Similar	Similar
	Alliance AFBC	Similar	Similar
	Georgetown AFBC	Lower	—
Fe	Exxon PFBC	Somewhat higher	Similar
	Alliance AFBC	Similar	Similar
	Georgetown AFBC	Similar	--
K	Exxon PFBC	Somewhat higher	Somewhat higher
	Alliance AFBC	Somewhat higher	Somewhat higher
	Georgetown AFBC	Similar	—
Li	Exxon PFBC	ND	Somewhat higher
	Alliance AFBC	Higher	Higher
	Georgetown AFBC	Higher	—
Mg	Exxon PFBC	Somewhat lower	Somewhat lower
	Alliance AFBC	Somewhat lower	Somewhat lower
	Georgetown AFBC	Similar	—
Mn	Exxon PFBC	Detection limit	Similar
	Alliance AFBC	Similar	Similar
	Georgetown AFBC	Similar	—
Mo	Exxon PFBC	Higher	Similar
	Alliance AFBC	Higher	Somewhat higher
	Georgetown AFBC	Similar	—
Na	Exxon PFBC	Somewhat higher	Somewhat higher
	Alliance AFBC	Somewhat higher	Somewhat higher
	Georgetown AFBC	Somewhat higher	—

(Continued)

TABLE 8-2. (Continued)

		Waste Leachate Compared to Media Leachate[1]	
Element/ Species	Waste	Lab[2]	Field[3]
Ni	Exxon PFBC	Similar	Similar
	Alliance AFBC	Similar	Similar
	Georgetown AFBC	Similar	—
pH	Exxon PFBC	Higher	Similar
	Alliance AFBC	Higher	Similar
	Georgetown AFBC	Higher	—
Si	Exxon PFBC	Somewhat lower	Somewhat higher
	Alliance AFBC	Somewhat lower	Somewhat higher
	Georgetown AFBC	Similar	—
Sr	Exxon PFBC	Higher	Similar
	Alliance AFBC	Higher	Higher
	Georgetown AFBC	Somewhat higher	—
SO_4	Exxon PFBC	Higher	Mixed
	Alliance AFBC	Higher	Mixed
	Georgetown AFBC	Higher	—
Ti	Exxon PFBC	Somewhat higher	Similar
	Alliance AFBC	Somewhat higher	Similar
	Georgetown AFBC	Similar	—
TDS	Exxon PFBC	Higher	Similar
	Alliance AFBC	Higher	Similar
	Georgetown AFBC	Higher	—
V	Exxon PFBC	Somewhat higher	Similar
	Alliance AFBC	Somewhat higher	Similar
	Georgetown AFBC	Similar	—
Zn	Exxon PFBC	Similar	Similar
	Alliance AFBC	Similar	Similar
	Georgetown AFBC	ND	—

[1] Descriptors:
Higher = More than an order of magnitude higher.
Somewhat higher = Visually higher, but not as much as an order of magnitude.
Similar = Visually in the same range.
Somewhat lower = Visually lower, but not as much as an order of magnitude.
Lower = More than an order of magnitude lower.
Mixed = Different parts of the plot show different results.
Detection Limit = Most of the values compared were at or near the detection limit.
ND = No data.

[2] Lab: Comparison of Step 1 and 2 leachates from waste with similar leachates from disposal media.

[3] Field: Comparison of waste-bearing cell leachates (upper sampling point) to leachates from control field cells containing disposal media only.

[4] Step 1 leaching of waste only.

conditions of the protocol, lab leaching columns, and field cells are quite different, particularly in the ratio of eluant volume to the mass of the waste. Thus, direct comparisons are of greatest utility for assessing the similarities and differences of the leachates under such different leaching conditions.

In the laboratory protocol comparison, which was performed using Step 1 and 2 leaching data for the waste and disposal media, most of the concentrations of the waste leachates were similar to or somewhat higher than the disposal media leachate concentrations. B, Ca, Li, Mo, Sr, SO_4, and TDS were generally significantly higher in the waste leachate than in the disposal media leachate. The pH of the waste leachates was also much higher than in the media leachates. Only the fluoride concentration was significantly higher in the media leachate than in the waste leachate (for the Alliance AFBC waste only).

In the field cell studies, the leachate data from the upper sample point of the field cells containing waste was compared to the leachate data from the control cells which contained disposal media only. Nearly all of the comparisons showed that the waste leachate and disposal media leachate were similar or only somewhat below or above each other in concentration. Only for Cl, Li, and Sr were the waste leachates more than an order of magnitude above the disposal media leachates in concentration. No parameter was generally as much as an order of magnitude lower for the waste than the disposal media in the field studies.

In addition to the visual comparison of the plotted concentrations, a more quantitiative comparison was performed for the protocol Step 1 leachates for the wastes and disposal media. In this comparison, a ratio was computed for the mean concentrations from Step 1 replicate leachates for the wastes and disposal media (Table 8-3). Values greater than one in this comparison indicate that the waste leachate had higher concentrations than the disposal media leachate. The parameters with the highest ratios are Ca, Li, Sr, SO_4, B, Mo, specific conductance, TDS, and Na. The lowest ratios were observed for Mg, Si, and Mn.

TABLE 8-3. RATIO OF FBC WASTE CONCENTRATION TO DISPOSAL MEDIA CONCENTRATION FOR PROTOCOL STEP 1 LEACHATES

Element/ Species	Shale			Interburden			Sandstone			Glacial Till			Alluvium			Limestone		
	Exxon PFBC	Alliance AFBC	Georgetown AFBC	Exxon PFBC	Alliance AFBC	Georgetown AFBC	Exxon PFBC	Alliance AFBC	Georgetown AFBC	Exxon PFBC	Alliance AFBC	Georgetown AFBC	Exxon PFBC	Alliance PFBC	Georgetown PFBC	Exxon PFBC	Alliance PFBC	Georgetown PFBC
B	180	59	2.7	150	51	2.3	-	-	-	210	71	3.2	-	-	-	-	-	-
Ba	1.7	1.1	1.6	2.3	1.4	2.1	3.6	2.3	3.4	1.4	0.93	1.4	2.8	1.8	2.7	1.7	1.1	1.7
Ca	32	26	29	61	49	55	23	18	21	78	62	70	1670	1340	1500	170	140	150
Co	-	-	-	4.1	0.55	0.069	15	2	0.25	-	-	-	-	-	-	-	-	-
Cr	6.0	8.0	3.3	0.67	0.89	0.37	5.0	6.7	2.8	-	-	-	-	-	-	-	-	-
Cu	-	-	-	0.23	1.6	0.34	4.0	28	6.0	-	-	-	-	-	-	-	-	-
F	2.5	0.64	0.41	7.7	3.0	1.3	2.8	0.74	0.47	0.93	0.24	0.16	11	2.8	1.8	0.91	0.24	0.15
Fe	3.5	1.5	0.36	0.81	0.34	0.085	-	-	-	-	-	-	-	-	-	-	-	-
K	54	9.4	3.8	52	9.1	3.7	32	5.6	2.3	-	-	-	-	-	-	32	5.6	2.3
Li	-	60	83	-	11	15	-	10	14	-	-	-	-	-	-	-	-	-
Mg	0.20	0.11	0.37	0.15	0.084	0.27	0.066	0.037	0.12	0.33	0.19	0.61	-	-	-	0.57	0.32	1.0
Mn	NC[a]	0.16	0.08	NC	0.11	0.054	NC	0.032	0.016	-	-	-	NC	0.69	0.35	-	-	-
Mo	-	-	-	-	-	-	-	-	-	164	28	1.3	-	-	-	12	2.1	0.1
Na	8.2	6.3	3.1	13	9.8	4.8	11	8.1	4.0	5.0	3.8	1.9	10.8	8.3	4.1	1.4	1.1	0.52
Ni	1.1	1.6	0.57	0.31	0.43	0.16	-	-	-	-	-	-	4.0	5.5	2.0	2.4	3.3	1.2
Si	0.34	0.15	0.64	0.09	0.041	0.18	0.26	0.11	0.49	0.33	0.14	0.62	0.23	0.1	0.43	0.38	0.16	0.71
SO_4	18	17	21	8.7	8.0	10.2	7.0	6.4	8.2	80	74	93	270	250	310	27	25	32
Sp. Cond.	23	23	22	27	27	26	16	16	16	54	54	52	200	200	190	39	39	37
Sr	22	160	110	14	110	68	15	110	73	100	2930	1880	-	-	-	8.4	62	40
TDS	19	23	24	14	16	17	7.50	8.8	9.3	80	95	100	210	250	270	25	30	31
Ti	-	-	-	-	-	-	1.0	6.4	1.2	-	-	-	-	-	-	-	-	-
TOC	0.64	0.60	1.9	2.1	1.9	6.2	1.8	1.7	3.5	0.27	0.26	0.82	0.55	0.52	1.7	1.1	1.0	3.4
V	-	-	-	-	-	-	4.5	13	1.0	-	-	-	-	-	-	-	-	-
Zn	6.5	2.0	0.5	0.51	0.16	0.039	-	-	-	8.7	2.7	0.67	-	-	-	-	-	-

NC[a] - Not calculated; disposal media concentration at or below detection limit.

Overall, the comparisons of the FBC waste leachates with leachates from the disposal media shows that the waste leachates can generally be expected to be higher in B, Ca, Li, Mo, Na, SO_4, Sr, and TDS. The pH, although very high in the waste leachates in the lab studies, was generally not elevated in the field studies. Chloride was higher for the Alliance AFBC wastes than for the disposal media. The parameters which were higher for the disposal media than for the waste were few and included only fluoride in the lab studies; no parameter was as much as an order of magnitude higher for the waste than the media in the field program.

8.3 Comparison of FBC Waste Leachate Quality With Water Quality Standards and Criteria

As a further means of evaluating the environmental acceptability of FBC wastes, the leachate concentrations that were observed were systematically compared to accepted water quality standards and criteria. The comparison was made for leachates that had not been exposed to disposal media samples and for leachates that had. The details of the comparison are given in Appendix I (Section I.7).

Opinion concerning "safe" ambient concentrations and concentrations in leachates and other discharges to the environment is quite varied. A survey of several authoritative sources was performed to form the basis of comparison for the FBC waste leachates. These sources include the Primary and Secondary Drinking Water Regulations (References 1 and 2), Resource Conservation and Recovery Act Regulations (Reference 3) and the Quality Criteria for Water (Reference 4). Table 8-4 sets forth the limits established in these sources for the important parameters in FBC waste leachate. Multimedia Environmental Goals (Reference 5) are included as potential indicators of monitoring trigger levels.

Also shown in Table 8-4 is the most stringent standard or criterion from the sources reviewed. In some instances, the most stringent value may not be applicable to likely avenues of FBC waste leachate discharge to the environment. The purpose of drawing a comparison in those instances is to

TABLE 8-4. WATER QUALITY STANDARDS AND CRITERIA REFERENCED FOR FBC WASTE LEACHATE QUALITY COMPARISONS[1]

Element/ Species	Primary or Secondary Drinking Water Regulation	RCRA Limit[2]	Quality Criteria for Water		Multimedia Environmental Goal (Discharge)[9]		Most Stringent Criterion
			Domestic Water Supplies (Health)	Freshwater Aquatic Life	Health	Ecology	
Al	–	–	–	–	8.0	1.0	1.0
As	0.05 (P)	5.0	0.05	–	0.25	0.05	0.05
B	–	–	–	–	47	25	0.75[10]
Ba	1.0 (P)	100.0	1.0	–	5.0	2.5	1.0
Be	–	–	–	0.011[3]	0.03	0.055	0.011
Ca	–	–	–	–	240	16	16.0
Cd	0.01 (P)	1.0	0.01	0.04[4]	0.05	0.001	0.001
Cl	250 (S)	–	250[7]	–	–	–	250
Co	–	–	–	–	0.75	0.25	0.25
Cr	0.05 (P)	5.0	0.05	1.0	0.25	0.25	0.05
Cu	1 (S)	–	1.0[5]	–	5.0	0.05	0.05
F	2.0 @ 60°F (P)	–	–	–	–	–	2.0 @ 60°F
Fe	0.3 (S)	–	0.3[5]	1.0	–	–	0.3
Hg	0.002 (P)	0.2	0.02	0.0005	0.01	0.25	0.0005
K	–	–	–	–	30	43	30
Li	–	–	–	–	0.33	0.375	0.33
Mg	–	–	–	–	90	87	87
Mn	0.05 (S)	–	0.05[5]	–	0.25	0.1	0.05
Mo	–	–	–	–	75	7.0	7.0
Na	–	–	–	–	–	–	–
Ni	–	–	–	–	0.23	0.01	0.01
Pb	0.05 (P)	5.0	0.05	–	0.25	0.05	0.05
pH[6]	6.5-8.5 (S)	–	5-9	6.5-9.0	–	–	6.5-8.5
Se	0.01 (P)	1.0	0.1	–	0.05	0.025	0.01
Si	–	–	–	–	–	–	–
SO_4	250 (S)	–	250[8]	–	–	–	250
Sp.Cond.[7]	–	–	–	–	–	–	–
Sr	–	–	–	–	46	–	46
TDS	500 (S)	–	250[8]	–	–	–	250
Ti	–	–	–	–	90	0.82	0.82
TIC	–	–	–	–	–	–	–
TOC	–	–	–	–	–	–	–
U	–	–	–	–	60	0.5	0.5
V	–	–	–	–	2.5	0.15	0.15
Zn	5 (S)	–	5.0[5]	–	25	0.1	0.1

[1] Concentrations in mg/L unless otherwise noted.

[2] RCRA = Resource Conservation and Recovery Act Regulations; 100 times the Primary Drinking Water Standard for Metals.

[3] For soft, not hard fresh water.

[4] For less sensitive aquatic life in soft water.

[5] Welfare, not health criterion.

[6] Units are standard pH units.

[7] Units are micromhos/cm.

[8] 250 mg/L is the criterion for chloride and sulfate (total) in domestic water supplies (welfare).

[9] Based on Minimum Acute Toxicity Effluent Level.

[10] Based on QLW long-term irrigation of sensitive crops.

emphasize where the FBC leachate concentrations do not exceed even the most stringent value. For many of the parameters, the most stringent criterion possibly is too low and could be increased to allow for dilution and dispersion of FBC leachate in the environment.

A summary of the results of the comparison with standards is given in Table 8-5 which contains the parameters for which the most stringent standard was consistently exceeded or was consistently not exceeded for each component of the laboratory and field programs.

This table shows that several parameters exceeded the standards in almost all phases of the study (both lab and field), including B, Ca, Cr, SO_4, and TDS. The standard for pH was exceeded in all phases of the lab investigation, and K, Mn, and Ni generally exceeded the standard for all phases of the field study. Ba, F, Fe, Mo, Sr, and Ti were generally below the standards for all phases of the investigation. Magnesium was below the standard for the lab studies. In the field studies, only pH was consistently below the standard (besides the parameters mentioned above for both the lab and field studies).

Close examination of the table shows little or no difference between the laboratory and field results in terms of parameters which were consistently above or below the standard. The three wastes are quite comparable in terms of the parameters consistently above or below the standard. There appears to be no significant difference in the field cells between cells containing disposal media only and cells containing both waste and disposal media.

TABLE 8-5. SUMMARY OF PARAMETERS WHICH CONSISTENTLY EXCEEDED OR WERE CONSISTENTLY BELOW THE MOST STRINGENT CRITERION OR STANDARD

Laboratory Investigations												Field Investigations									
Exxon PFBC				Alliance AFBC				Georgetown AFBC				Exxon PFBC				Alliance AFBC					
Generation		Attenuation		Generation		Attenuation		Generation		Attenuation[3]		Upper Sample Point		Lower Sample Point		Upper Sample Point		Lower Sample Point		Field Control Cells	
E[1]	B[2]	E	B	E	B	E	B	E	B	E	B	E	B	E	B	E	B	E	B	E	B
B	As	B	Ba	Al	Ba	B	Ba	Ca	Al	SO_4	Ba	B	Ba	Al	Ba	B	Ba	Al	Ba	Ca	Ba
Ca	Ba	Ca	Cl	B	Co	Ca	Cl	pH	Cl		Cd	Co	F	B	Cl	Ca	Co	B	Co	Cr	Cl
Cr	Cd	Cr	F	Ca	F	Cd	Co	TDS	Co		Cr	Cr	Fe	Ca	F	Cl	F	Ca	F	Mg	F
pH	Cl	Co	Li	Cd	Fe	Cr	F		Cu			Mg	Mo	Cr	Fe	Cr	Mo	Cl	Li	Mn	Fe
SO_4	Co	Cu	Mg	Cr	Mg	Cu	Fe		F			Mn	Sr	Mg	Li	Li	Sr	Mn	Mo	K	Li
TDS	Cu	Ni	Sr	Cu	Mn	Ni	Mg		Fe			Ni	Ti	Mn	Mo	K	Ti	Ni	K	SO_4	Mo
Zn	F	K	Ti	K	Mo	K	Mo		K			K	pH	Ni	Sr	SO_4	Zn	K	Sr	V	Sr
	Fe	SO_4		Ni	Ti	SO_4	Sr		Mg			SO_4		K	Ti			SO_4	Ti	Zn	Ti
	K	pH		pH	Zn	V	Ti		Mn			V		SO_4	pH			TDS	pH	TDS	pH
	Mg	TDS		SO_4		pH	Zn		Mo			TDS		V							
	Mn			TDS		TDS			Sr					TDS							
	Mo			V					Ti												
	Pb								Zn												
	Se																				
	Sr																				
	Ti																				
	V																				

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[1] E = Consistently exceeds the most stringent criterion or standard (approximately 50% or more).

[2] B= Consistently below the most stringent criterion or standard (approximately 10% or less).

[3] Based on only two data points.

9.0 STATISTICAL PREDICTION OF FIELD LEACHING AND ATTENUATION BEHAVIOR BASED ON OBSERVED LABORATORY RESULTS

Two empirical approaches were taken to predict the chemical behavior of FBC wastes after disposal in landfills. Both approaches involved the development of statistical models from laboratory leaching data to predict field leachate properties. An extensive statistical analysis of leaching and attenuation data for Exxon PFBC and Alliance AFBC waste was performed in the first approach. A more limited feasibility study for the second statistical approach employs only leaching data for the Exxon PFBC waste. The second approach could be extended to analyze attenuation data also, but was not attempted within the scope of this study. Details of the development of the predictive models are given in Appendix G.

The two statistical approaches are similar in the following respects:

1. Laboratory data were used to develop models for predicting concentrations (or a function thereof) of the different chemical species. In this step, field data are not used.

2. The model development was accomplished by using regression analysis.

3. A separate model was ultimately produced for each chemical species. In the leaching models, concentration was expressed as a function of volume per mass. In the attenuation models (discussed in the first but not the second approach), fractional attenuation was also expressed as a function of volume per mass. Either approach could be used to develop attenuation models in which concentration is expressed as a function of volume per mass.

4. Thus, the end result of both approaches is the same: a model to predict concentration (or a function thereof) as a function of volume per mass. Since volume per mass is a normalized quantity, the models can be used to predict field conditions.

The methods differ in the steps used to develop the statistical models. In the first approach, a model is developed directly to predict the concentration of a particular species as a function of volume per mass. The concentrations of other species do not come into play.

In the second approach, a regression model is first developed in which the concentration of a chemical species is predicted in terms of the concentrations of other chemical species at the preceding leaching step and possibly pH at the preceding or current leaching step. Subsequently, transformations are made through a set of mathematical steps to produce models which predict concentration as a function of volume per mass. Thus, for simplicity, the two approaches can be referred to as the direct and indirect methods, respectively.

For the sole purpose of developing a model which predicts concentration in terms of volume per mass, the direct method is simpler and less demanding both in terms of labor and computer time. Moreover, the direct method as formulated ensures that non-negative, real-valued leaching concentrations are predicted.

On the other hand, the indirect method produces intermediate results which can be interpreted from the point of view of causal relationships in the leaching process. Suppose, for example, that the concentration of species i is selected as a predictor of species j. This may imply that the presence of species i in the leachate affects the leaching of species j from the waste. It must be remembered, however, that statistical correlations do not automatically imply that a cause and effect relationship exists. A disadvantage of the indirect method is that it is possible for instabilities to develop.

In each approach, model development to predict leaching behavior was successful. Agreement was achieved between the laboratory predicted values and the data from which the models were developed. The agreement is described below in terms of tables of statistical measures. Extensive sets of plots comparing observed and predicted concentrations for each model development method are presented in Appendix G.

In connection with the direct method, extensive summary measures of agreement between observed and predicted field leachate concentration values are presented. It is shown that field observed values and predictions from the laboratory models agree within an order of magnitude for most chemical species and waste combinations. For the indirect method, observed and predicted field concentration values are compared through plots of cumulative mass leached.

As noted, models for fractional attenuation were developed using only the direct method. Agreement between field observed and predicted values was achieved only in isolated cases. It is possible that in future work, better agreement will be achieved if concentration, rather than fractional attenuation, is used as the dependent variable.

This section is a summary of the model development results; the details are presented in Appendix G.

9.1 Leaching and Attenuation Models Developed Through Regressions On Volume per Mass

In the direct method, statistical models were developed to characterize both leaching and attenuation behavior. The primary objective of the models was to determine the feasibility of predicting field leachate concentration values from laboratory data.

The investigation was performed using the following waste and disposal medium combinations:

1. Exxon PFBC waste and shale, sandstone, glacial till, alluvium, and limestone media; and

2. Alliance AFBC waste and shale, interburden, alluvium, and limestone media.

Thus, a reasonable variety of waste-medium combinations were represented in the data base. The disposal media affect the leaching results only in that the medium comprises the uppermost layer in the field cells. The contents of the field cells used in this part of the modeling study are indicated in Table 9-1.

TABLE 9-1. CONTENTS OF FIELD CELLS USED IN MODELING STUDY

Cell No.	Waste	Disposal Medium
1, 2	Exxon PFBC	Shale
3	Exxon PFBC	Glacial Till
4	Exxon PFBC	Limestone
5	Exxon PFBC	Alluvium
6	Exxon PFBC	Sandstone
13	Alliance AFBC	Interburden
14, 15	Alliance AFBC	Alluvium
16	Alliance AFBC	Limestone
17	Alliance AFBC	Shale

Note: Two control cells (Cells 7 and 12) were also operated, but these were not used in the modeling study. Cell 7 contained shale and Cell 12 contained alluvium.

First, an analysis of leaching behavior was performed. Models were developed from laboratory data to predict leachate concentrations. When these models were developed, certain chemical species whose concentrations were predominantly near or below detection limits were excluded. Subsequently, an analysis was performed to quantify the agreement between observed field concentration and corresponding values predicted from the laboratory models. It was found that for the 13 species investigated in leachates from the Exxon PFBC waste, the mean agreement between the observed field values and the laboratory-predicted field values was within a factor of 10 in 11 cases, a factor of 5 in eight cases, and a factor of two in three cases. For 19 species investigated in leachates from the Alliance AFBC waste, the mean agreement was within a factor of 10 in 17 cases, a factor of five in 16 cases, and a factor of two in 10 cases. Thus, laboratory models are capable of predicting field trends within an order of magnitude in most cases. The difference between the laboratory-predicted and field-observed values was statistically significant for most species, however. It was verified through plots of observed and predicted values and statistical measures that the models fit the laboratory data.

The prediction of field data involved an extrapolation, since the laboratory volumes of leachate per unit mass of waste were larger than the field cells. Further investigation showed, however, that the differences between field-observed and laboratory-predicted values are not attributable wholly or predominantly to the extrapolation. Actual differences between the behavior of the laboratory and field chemical systems are believed to explain a significant part of the discrepancies between observed and predicted values.

An analysis was also performed of fractional attenuation, which (as noted in Section 6.0) is the fractional reduction in leachate concentration due to contact with the disposal medium. It was observed from raw data plots that prediction of field fractional attenuations from laboratory models was infeasible for the majority of cases. This is due to the dissimilarity of the lab and field trends and random scatter in the fractional attenuation data. Successful predictions of field behavior from laboratory data for a few species were accomplished, however.

9.1.1 Models for Leaching

Laboratory data from protocol Step 1, 2, and 3 and field data from the upper sampling points of the field cells were used to develop models for leaching behavior. As noted, the investigation was performed using the following waste and disposal medium combinations: 1) Exxon PFBC waste and shale, sandstone, glacial till, alluvium, and limestone medial; and 2) Alliance AFBC waste and shale, interburden, alluvium, and limestone media.

For the leaching studies the following were the primary questions addressed:

1. Is it possible to develop models to fit the laboratory data?

2. Is it possible to use the laboratory models to predict field leaching concentrations?

9.1.2 Calculation of Volume per Mass

The volume per unit mass (referred to here as "volume per mass") is the volume of liquid which has contacted the waste per unit mass of waste contacted. Normalizing the leachate volume by the mass of waste provides an independent variable which has a consistent meaning for the laboratory and field data and also facilitates comparisons. The field volume per mass is simply the flow-through volume divided by the mass of waste in the cell. For the laboratory, the volume per mass for protocol Step 1 is 10 mL/g. For Step 2, iteration i, the volume per mass is $(i+1)10$; the same mass is retained, but Step 1 leachate is added each iteration. For Step 3, iteration i, the volume per mass is $10/(i+1)$; fresh waste is added each iteration, but the same leachate is retained.

9.1.3 Data Selection

Models were not developed for the chemical species for which all or virtually all leachate concentrations were near or below the detection limits for the analytical instrument used nor should they be necessary. There was no basis for developing meaningful models for these cases. Models were developed for Al, B, Ba, Ca, Cl, Cr, F, Fe, Na, Si, Sr, SO_4, TDS, and Zn for the Exxon PFBC waste and for Al, B, Ba, Be, Ca, Cd, Cl, Cr, Cu, F, Fe, Li, Mn, Mo, Na, Ni, Si, SO_4, Sr, Ti, TDS, V, and Zn for the Alliance AFBC waste. For these species, field data were also available for 13 species for the Exxon PFBC and for 19 species for the Alliance AFBC waste. Additional discussion pertaining to data selection for leaching model development is presented in Appendix G.

9.1.4 Methods Used to Develop Laboratory Leaching Models

The functional form used in developing the models from the laboratory data is a best-fit exponential polynomial as follows:

$$C = 10^{b_0 + b_1V + b_2V^2 + b_3V^3}$$

where:

C is concentration (mg/L),

b_0, b_1, b_2, and b_3 are regression coefficients, and

V is volume per mass of waste (mL/g).

It should be noted that if $b_2 = b_3 = 0$, the model has the form:

$$C = 10^{b_0}\ 10^{b_1V} = (B)\ 10^{b_1V}$$

where $B = 10^{b_0}$.

Thus, the model can take the form of a decaying exponential (when $b_1 < 0$ in the expression above) or it can have a variety of other shapes, depending on the values of the b_i. The versatility of the functional form used is one reason for its selection. In any case, the model can be expressed as:

$$C = (10^{b_0})\ (10^{b_1V + b_2V^2 + B_3V^3})$$

Thus, b_0 determines a constant multiplier for the predicted concentrations, and b_1, b_2, and b_3 determine the shape of the curve as a function of volume per mass.

As written above, the model is nonlinear in the coefficients to be determined. Taking the logarithm of both sides of the equation, however, produces an equation which is linear in the coefficients:

$$\log_{10}(C) = b_0 + b_1V + b_2V^2 + b_3V^3$$

Expressing the model in this form allows linear regression techniques to be used; thus, a closed-form expression exists for the regression coefficients. If nonlinear regressions were used, an iterative solution would ordinarily be required, which would increase the computer time needed. Additionally, lack of convergence would be a possibility. Statistical variable selection methods were used to choose the actual terms for inclusion in each model. If any of the candidate terms V, V^2, and V^3 did not contribute significantly to the predictive accuracy, it was excluded.

9.1.5 Laboratory Leaching Models

Tables 9-2 and 9-3 present the models developed for leaching concentrations for Exxon PFBC and Alliance AFBC wastes, respectively. In the tables, the following statistical terms are used to describe the models.

N - sample size (i.e., the number of points used),

R^2 - square of the multiple correlation coefficient, discussed below,

standard error - standard deviation of the fluctuations of logarithms of concentrations (mg/L) about the regression line (i.e., the standard deviation of the observed minus predicted values),

b_0, b_1, b_2, and b_3 - regression coefficients, discussed above, and

standard errors of b_1, b_2, and b_3 - standard errors of the regression slopes, b_1, b_2, and b_3; the standard error of a quantity is the standard deviation of its error.

As is discussed above, the regression analysis was performed after a logarithmic transformation to linearize the model in terms of the coefficients. Thus, R^2 and the standard error are both measures of the agreement between logarithms of concentrations and the corresponding predicted values.

The quantity R^2 is the fraction of the variance in the logarithms of the concentrations which is explained by the model. The standard error is the standard deviation of the differences between the observed and predicted values in log-space.

TABLE 9-2. MODELS FOR LABORATORY LEACHING FOR EXXON PFBC WASTE

Element/ Species	N	R^2	Standard Error	b_0	b_1	Standard Error of b_1	b_2	Standard Error of b_2	b_3	Standard Error of b_3
Al	14	0.11	0.17	-0.48	0.028	0.024	-0.00077	0.00069	—[1]	—
B	14	0.91	0.058	1.7	-0.082	0.0082	0.0022	0.00024	—	—
Ba	14	0.82	0.086	-0.33	-0.057	0.012	0.0012	0.00035	—	—
Ca	14	0.50	0.053	3.2	0.022	0.021	-0.0026	0.0015	0.000063	0.000031
Cl	13	0.91	0.16	2.1	-0.25	0.064	0.0097	0.0046	-0.00011	0.000095
Cr	13	0.49	0.32	0.25	-0.28	0.13	0.017	0.0094	-0.00030	0.00019
F	13	0.59	0.21	-0.18	0.089	0.083	-0.010	0.0061	0.00024	0.00013
Fe	14	0.0053	0.17	-0.73	0.0014	0.0054	—	—	—	—
Na	14	0.61	0.20	2.6	-0.26	0.077	0.016	0.0056	-0.00028	0.00012
Si	14	0.29	0.15	-0.47	0.037	0.021	-0.00089	0.00062	—	—
Sr	14	0.56	0.16	1.0	-0.12	0.065	0.0060	0.0047	-0.00098	0.000097
SO_4	14	0.44	0.018	3.1	-0.0036	0.0025	0.00014	0.000072	—	—
TDS	14	0.49	0.077	3.6	-0.0082	0.0024	—	—	—	—
Zn	14	0.38	0.17	-1.7	0.86	0.067	-0.0081	0.0049	0.00019	0.00010

Note: Volume per Mass $\leq$30 mL/g

[1] Since variable selection techniques were used in the model development, not all terms were included in all models. Dashes indicate excluded terms.

TABLE 9-3. MODELS FOR LABORATORY LEACHING FOR ALLIANCE AFBC WASTE

Species	N	R^2	Standard Error	b_0	b_1	Standard Error of b_1	b_2	Standard Error of b_2	b_3	Standard Error of b_3
Al	23	0.77	0.16	0.15	−0.094	0.034	0.0052	0.0031	−0.00011	0.000069
B	24	0.60	0.24	0.85	−0.17	0.052	0.012	0.0046	−0.00024	0.00010
Ba	23	0.19	0.30	−0.83	—[1]	—	−0.0069	0.00031	—	—
Be	21	0.67	0.19	−1.6	−0.34	0.13	0.033	0.017	−0.00090	0.00052
Ca	22	0.047	0.061	3.2	−0.0015	0.0015	—	—	—	—
Cd	20	0.85	0.095	−1.1	−0.095	0.012	0.0033	0.00059	—	—
Cl	24	0.99	0.053	2.6	−0.11	0.0045	0.0016	0.00015	—	—
Cr	24	0.94	0.087	−0.31	−0.20	0.019	0.013	0.0017	−0.00025	0.000039
Cu	24	0.68	0.19	−0.61	−0.17	0.042	0.012	0.0037	−0.00023	0.000085
F	24	0.45	0.15	−0.86	−0.084	0.033	−0.0051	0.0030	0.000080	0.000067
Fe	22	0.83	0.092	−0.77	−0.21	0.060	0.019	0.0074	−0.00052	0.00024
Li	24	0.99	0.033	0.46	−0.19	0.0073	0.010	0.00065	−0.00019	0.00015
Mn	24	0.67	0.14	−1.5	−0.13	0.032	0.0093	0.0028	−0.00019	0.000064
Mo	24	0.99	0.020	−0.11	−0.044	0.0045	0.0017	0.00040	−0.000033	0.0000090
Na	24	0.99	0.040	2.1	−0.20	0.0089	0.011	0.00079	−0.00020	0.000018
Ni	20	0.91	0.057	−0.68	−0.12	0.042	0.0086	0.0052	−0.00019	0.00017
Si	24	0.66	0.097	−0.26	−0.016	0.0024	—	—	—	—
SO_4	24	0.77	0.014	3.1	−0.019	0.0031	0.0012	0.00028	−0.000021	0.0000063
Sr	22	0.90	0.086	1.6	−0.029	0.0021	—	—	—	—
Ti	24	0.71	0.15	−0.28	−0.15	0.033	0.0097	0.0029	−0.00019	0.000066
TDS	24	0.92	0.0073	3.6	−0.0065	0.00061	0.00013	0.000020	—	—
V	24	0.63	0.16	−0.35	−0.14	0.036	0.0089	0.0032	−0.00017	0.000072
Zn	22	0.81	0.091	−1.0	−0.15	0.060	0.011	0.0074	−0.00025	0.00023

Note: Volume per Mass ≤ 30 mL/g

[1] Since variable selection techniques were used in the model development, not all terms were included in all models. Dashes indicate excluded terms.

In a few instances, the R^2 value is very low, but the standard error is also low. In these instances, the original variance of the lab concentrations is low; hence, a model which explains a small fraction of the original variance (low R^2) can still be in good agreement with the observed values (low standard error). Thus, a low R^2 value does not necessarily imply that the model is not good.

9.1.6 Comparison of Predicted Values From Laboratory Models and Field Concentrations

The agreement between values predicted from the laboratory models and the corresponding field concentrations was analyzed through plots and various tabulated statistical measures. A comparison of field observed and predicted values was also made by use of statistical measures. The plots and statistical measures are presented in detail in Appendix G.

Tables 9-4 and 9-5 present the average ratios of predicted to observed field values. If the field observed and predicted values agreed perfectly on the average, the average ratio would be exactly one. In cases in which the ratio is between 0.1 and 10, the observed and predicted values agree within a factor of 10 on the average.

To quantify the amount of scatter in the field observed minus predicted values, the standard deviation of the field residual values was computed for each element or species. The scatter was found no more than ± factor of three in all of the 13 cases for the Exxon PFBC leachate and in 14 of 19 cases for the Alliance AFBC leachate. The scatter is extreme (± a factor of 41) only for calcium for Alliance AFBC leachate. Random scatter of ± a factor of three or less was achieved in 27 of 32 cases, or 84 percent of the models.

In the majority of the cases, the mean agreement between field-observed and laboratory-predicted values is less than a factor of 10, and the random scatter of the residuals is less than a factor of three.

TABLE 9-4. COMPARISON OF FIELD CONCENTRATIONS AND VALUES PREDICTED BY MODEL DEVELOPED FROM LABORATORY DATA FOR EXXON PFBC WASTE LEACHATE

Species	Number of Points (Lab)	Number of Points (Field)	Mean* Observed/Predicted Field Concentration
Al	14	-	-
B	14	125	0.11
Ba	14	64	0.16
Ca	14	125	0.32
Cl	13	30	0.67
Cr	13	122	0.045
F	13	123	0.32
Fe	14	82	0.32
Na	14	69	0.31
Si	14	125	85
SO_4	14	117	3.0
Sr	14	125	0.12
TDS	14	123	1.7
Zn	14	48	1.0

*Geometric mean (See Appendix G for details)

TABLE 9-5. COMPARISON OF FIELD CONCENTRATIONS AND VALUES PREDICTED BY MODEL DEVELOPED FROM LABORATORY DATA FOR ALLIANCE AFBC WASTE LEACHATE

Species	Number of Points (Lab)	Number of Points (Field)	Mean* Observed/Predicted Field Concentration
Al	23	37	0.58
B	24	42	0.12
Ba	23	49	1.5
Be	21	–	–
Ca	22	54	0.011
Cd	20	–	–
Cl	24	52	0.70
Cr	24	34	0.20
Cu	24	11	0.24
F	24	51	1.3
Fe	22	10	1.6
Li	24	40	0.85
Mn	24	18	1.8
Mo	24	11	0.47
Na	24	54	1.1
Ni	20	–	–
Si	24	54	22
SO_4	24	52	1.0
Sr	22	53	0.47
TDS	24	52	0.88
Ti	24	3	0.26
V	24	4	0.22
Zn	22	–	–

*Geometric mean (See Appendix G for details).

9.1.7 Modeling of Fractional Attenuation

It was found that prediction of field fractional attenuation (A_F) values by models developed from laboratory (A_L) values was not possible in most cases. The reasons were scatter in the fractional attenuation data and dissimilarity in the trends observed in the field and the lab. It should be mentioned that fractional attenuation is a derived quantity, involving concentrations before (C_b) and after (C_a) contact with the disposal medium:

$$A = \frac{C_b - C_a}{C_b}$$

If C_b and C_a are small (say, near the detection limit), the ratio can have a large uncertainty. Due to division by the small value C_b, the ratio can be large in magnitude even when the concentrations are small. This problem was addressed in part by not developing models for species with predominantly undetected C_b values; this exclusion was no sacrifice, since the fractional attenuation is not of practical importance if the concentration before contact with the medium is very low or undetected.

In view of the comments above, it is felt that further research would be beneficial to determine whether field values of C_a itself, or some derived measure of field attenuation other than fractional attenuation, could be predicted by laboratory models.

9.2 Multi-Species Models Transformed to be a Function of Volume Per Mass

A second approach for predicting field behavior in terms of models developed from laboratory data was also attempted. Models for Exxon PFBC waste leaching results only are presented. However, the same approach could be applied to the data for other wastes and could be extended to develop attenuation models. As formulated, the model development requires points equally spaced in volume per mass. Thus, protocol Step 1 and 2 data, which satisfy this criterion, were used. Subsequent prediction of concentration as a continuous function of volume per mass is possible, however. A model is presented for (normalized) concentration as a function of volume per mass for each species considered. High R^2 values, above 0.9 in most cases, were achieved, indicating very good agreement between the predicted values and the laboratory data from which the models were developed. The quantity R^2, the square of the multiple correlation coefficient, can be interpreted as the fraction of the variation in the dependent variable which can be explained by the model.

Predictions made with the models are compared to the corresponding observed leaching values for field Cell 1 to test the modeling results. For this comparison, the concentrations were transformed to cumulative mass leached per mass of original waste. The comparison was made by presenting a plot of observed and predicted values for each model developed. The complete set of plots is presented in Appendix G. Barium and strontium concentrations in the field cell leachates were predicted well, and zinc was predicted nearly as well. Sulfate was predicted within a factor of two, and calcium and chromium were predicted within a factor of three. In most cases, predicted values were higher than observed values; the exceptions were sulfate, silicon, and sodium.

At an intermediate step, models were obtained such that the concentration for a given species in the i^{th} laboratory leaching extraction could be predicted in terms of the concentrations of a selected subset of the chemical species in the preceding (i.e., $(i-1)$st) extraction and possibly pH at the preceding or current extraction. Selection of the predictor variables included in each model was made by statistical model development techniques.

These models, then, can be used as a means for chemical interpretation of the causal relationships in the leaching process. For example, if the concentration of species i is selected as a predictor of the concentration of species j, this may imply that the presence of species i in the leachate affects the leaching of species j from the waste. As always, however, it must be remembered that statistical correlations do not automatically imply that a cause-and-effect relationship exists. Chemical reasoning must supplement the statistical results in each case to identify the most likely causal relationships. A possible extension of the work presented here would include the formulation of theorized sets of causal relationships and subsequent use of statistical relationships to verify or refine the theory.

With the above mentioned points in mind, the following deductions having chemical significance were made from the modeling results. The species were classed into two groups. In the first indirect group, consisting of SO_4, Si, Cr, Ba, Na, Fe, Ca, Zn, and Sr, the species are self-controlled; that is, the concentration at the i^{th} extraction of one of these species is related to leading concentrations of species within the group. Sulfate and silicon are individually self-controlled. Concentrations for the second group, consisting of Mg, B, F, Cl, and Al, are largely controlled by the first group.

It was observed that pH did not play a crucial role as a predictor variable. This is not surprising, since pH varied only between 11.0 and 12.0 during the sequence of laboratory extractions for the Exxon PFBC waste.

The multi-species modeling approach presented in this section was developed by an independent consultant, Dr. James Dunn, Professor of Statistics at the University of Arkansas and formerly a statistician at the Environmental Protection Agency.

9.2.1 Methods Used to Develop Models

As is discussed above, in the model development the concentration of a given species at step i was expressed as a function of concentrations observed at the preceding step (step i-1). That is,

$$Y_k^{(i)} = \sum_j A_j Y_j^{(i-1)}$$

where $Y_k^{(i)}$ is the concentration of species k at step i,

$Y_j^{(i-1)}$ is the concentration of species j at step i-1, and

A_j is a coefficient to be determined by using regression analysis.

To illustrate the meaning of the equation above, consider the following model for barium concentration: $B_a^{(i)} = 0.246\ (Cr^{(i-1)}) + 0.681\ (Ba^{(i-1)})$.

This equation states that the barium concentration at step i ($Ba^{(i)}$) can be predicted as a linear function of the chromium ($Cr^{(i-1)}$) and barium ($Ba^{(i-1)}$) concentrations at step i-1. Statistical variable selection techniques were used to determine which terms should be included in each model. Only terms which contributed significantly to the predictive accuracy were included.

The equation above can be altered to include pH. However, as is discussed above, it was found that pH did not contribute very much to the predictive accuracy of the models (see Appendix G).

9.2.2 Laboratory Leaching Models

Table 9-6 indicates the terms used as predictors for each species. As is discussed above, the first group, consisting of SO_4, Si, Cr, Ba, Na, Fe, Ca, Zn, and Sr are self-controlled in that each is predicted in terms of others in the group. Members of the second group are predicted by members of the first group.

Table 9-7 presents the coefficients and the R^2 values obtained for each equation. The R^2 values are very high, with all values above 0.9. However, this is at least partly because of the large number of predictor variables considered; for each species, the leading concentrations of the 13 chemical species considered were candidate predictor variables. The danger in employing a large number of possible predictors is that one of them may correlate with the dependent variable by random chance, artifically inflating

TABLE 9-6. RELATIONSHIPS BETWEEN CONCENTRATIONS AND THEIR PREDICTORS

Dependent Variable	Variables Whose Leading Values Are in the Model												
	SO_4	Si	Cr	Ba	Na	Ca	Zn	Sr	Mg	B	F	Cl	Al
SO_4	X												
Si		X											
Cr	X				X	X	X	X					
Ba			X	X									
Na			X					X					
Fe	X			X	X	X							
Ca			X										
Zn					X		X	X					
Sr			X	X		X							
Mg													
B			X					X					
F	X												
Cl					X	X			X		X		
Al		X											

TABLE 9-7. ESTIMATED VALUES OF NON-ZERO COEFFICIENTS AND ASSOCIATED R^2 V

Element/ Species	Predictor	Coefficient	R^2
SO_4	SO_4	0.9805	0.990
Si	Si	1.3485	0.963
Cr	SO_4	-0.00011	0.942
	Na	0.01274	
	Fe	0.42481	
	Zn	2.31065	
	Sr	0.17787	
Ba	Cr	0.246	0.969
	Ba	0.681	
Na	Cr	134.140	0.931
	Sr	11.892	
Fe	SO_4	-0.000103	0.911
	Na	-0.00535	
	Ba	3.363	
	Fe	0.509	
Ca	Cr	3232.632	0.941
	Ca	0.709	
Zn	Na	0.00687	0.926
	Zn	-2.055	
	Sr	0.0746	
Sr	Cr	5.739	0.983
	Ba	8.041	
Mg	Fe	2.058	0.924
	Ca	0.000160	
B	Cr	35.575	0.911
	Sr	4.27	
F	SO_4	0.000302	0.907
Cl	Na	-0.180	0.977
	Fe	5.657	
	Ca	0.0063	
	Mg	2.803	
	F	9.678	
Al	Si	0.875	0.946

the R^2 value. In the direct method, only three candidate predictors were used, V, V^2, and V^3. Thus, the R^2 values obtained through the direct and indirect methods are not comparable.

The derivation of models which predict concentration as a function of volume per mass from models in the form discussed above is given in Appendix G. Also, extensive plots of observed and predicted cumulative concentrations as a function of volume per mass are presented.

9.3 Summary

The direct method of establishing a rigorous, statistically-based relationship between the laboratory-predicted and actual field cell concentrations for several species was reasonably successful for the leachate generation phase. For the attenuation phase, however, the method was not able to establish a reliable relationship between the lab and field results.

For the 13 species investigated for the Exxon PFBC waste leachates, the agreement between the observed field values and the laboratory-predicted field values was within a factor of 10 in 11 cases, a factor of five in eight cases, and a factor of two in three cases. For the 19 species investigated for the Alliance AFBC waste leachates, the agreement was within a factor of 10 in 17 cases, a factor of five in 16 cases, and a factor of two in 10 cases.

The objectives in investigating the indirect approach were more limited than was the case for the direct approach. The lab protocol results, from Steps 1 and 2 leaching of Exxon PFBC waste were used with the results from one of the PFBC field cells. Three parameters were predicted closely, and three others were predicted within a factor of three for the leachate generation phase. An attempt to establish a similar relation for other field cells in the generation phase or for all cells in the attenuation phase was outside the scope of the investigation.

10.0 COMPATIBILITY OF LANDFILL LINER MATERIALS WITH FBC WASTE LEACHATE

Analyses to date indicate that FBC wastes in general are nonhazardous (Section 5.0) and will be disposed of in a nonsecure landfill. In the event that some future FBC waste streams are classed as hazardous, a preliminary investigation was made of the compatibility of commonly used landfill liner materials with FBC waste leachate. Some of the future non-hazardous FBC waste landfills may also have landfill liners incorporated in their design and construction.

The objective of this investigation was to use several chemical and physical tests to determine whether the composition is changed or strength is reduced as a result of exposure to FBC waste leachate. Six synthetic liner materials and one clay were tested:

- Neoprene;
- Polyvinyl chloride (PVC);
- Chlorinated polyethylene (CPE);
- Chlorosulfonated polyethylene (Hypalon);
- Butyl rubber;
- Ethylene propylene diene monomer (EPDM) rubber; and
- Sodium bentonite clay.

These liners were chosen because they are commonly used and they have been studied quite extensively as liner materials. Exxon PFBC waste leachate from the laboratory protocol (Step 1, 7-day) was used throughout the experiment. The initial composition of this leachate is shown in Table 10-1.

TABLE 10-1. COMPOSITION OF EXXON PFBC WASTE STEP 1 7-DAY LEACHATE USED FOR THE LINER COMPATIBILITY STUDY[1]

Element/Species	Concentration
Ag	0.003
Al	0.61
As	0.04
B	13
Ba	0.17
Ca	1700
Cd	0.0025
Cl	4.5
Cr	0.062
Cu	0.003
F	0.79
Fe	0.22
K	20
Mg	1.9
Mn	0.001
Na	17
Ni	0.014
Pb	0.035
pH[2]	11.8
Se	0.06
Si	0.67
SO_4	1230
Sp. Cond.[3]	9530
Sr	290
TDS	3210
TOC	1.1
Ti	0.00001
U	0.15
V	0.005
Zn	0.17

[1] Concentration is in mg/L unless otherwise noted.

[2] Units are standard pH units.

[3] Units are micromhos/cm.

10.1 Procedures for the Synthethic Liner Study

The susceptibility of the synthetic liners to chemical attack by leachate was the key consideration in the investigation, since any satisfactory liner can be assumed to be essentially impermeable unless it is degraded in some manner. In order to meet the objectives of this study and meet the 18-month timeframe limitation, an accelerated testing procedure which was also simple in design was used. A batch immersion design was thus employed which exposed both sides of the liner strips to the leachate. The leachate was not circulated or agitated as the experiment proceeded. The design (Figure 10-1) consisted of a glass tank fitted with a glass rack to hold the liner strips suspended in the leachate. A separate tank was used for each liner type. Each invididual liner strip was one inch wide and by six inches long. The tanks were initially filled to the brim, sealed with a glass plate taped to the top of the tank, and kept in darkness.

Enough strips of each liner type were included in the experiment to allow three per month for 18 months to be removed. The interaction of the leachate and liners was evaluated by monitoring three parameters:

- Tensile strength as an indication of the structural stability of the liners;
- Liner surface characteristics as determined by scanning electron microscope (SEM) observation to detect any changes in the microstructure of the liner surfaces; and
- Total organic carbon (TOC) concentration in the leachate contacting the liners to monitor levels of possible organic degradation products produced with time.

The tensile strength and surface characteristics were also determined on liner samples prior to contact with the leachate for purposes of comparison. Although the initial air space in the tanks was minimized, this air space

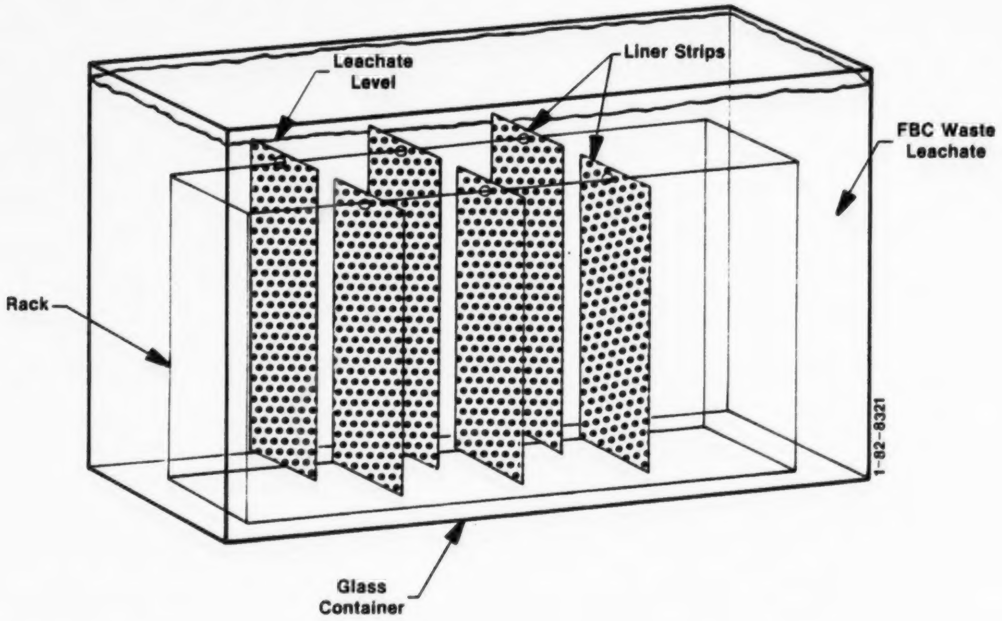
Leachate Level
Liner Strips
FBC Waste Leachate
Rack
Glass Container
1-82-8321

Figure 10-1. Batch Immersion Design for Exposure of Synthetic Liners to Exxon PFBC Waste Leachate.

increased as samples were removed for TOC analysis as the experiment proceeded.

10.1.1 Tensile Strength

Major changes in tensile strength were used as indicators of liner degradation by the FBC waste leachate. The tensile strength of a material is defined as the stress required to cause permanent deformation. The method used to determine the tensile strength of the liners was ASTM Method D-412. In this method, liner strips of the same dimensions (1 in x 6 in) were secured in a tensile strength tester and stretched until they broke or were permanently deformed. Method D-412 is reported to measure the applied force to within ± 2%, which results in a tensile strength precision of ± 10% (considering the variation in the width and cross-sectional area of the liner strips). Each month, three strips of each liner material were tested, resulting in triplicate measurements of the tensile strength.

10.1.2 Liner Surface Characteristics

Scanning electron micrographs of representative portions of the liners were obtained to determine the surface morphology of the strips initially (before leachate contact) and each month as the experiment proceeded. Small pieces of the polymer were mounted on discs using silver paint as the adhesive. Scanning electron micrographs were obtained at a lower and a higher magnification (500X and 5000X). Each liner strip was examined before leaching and again after 16 months of exposure to the leachate.

Two problems emerged during SEM observation of the synthetic liner surfaces. As the immersive test proceeded, a white precipitate began to form on the bottom on the immersion tanks and on the liner strips themselves. This precipitate, which was probably calcium carbonate and possibly calcium oxide, impeded the observation of the liner surfaces. It was therefore necessary to try to remove the crystalline material without disturbing fragile, possibly oxidized polymer layers on the surface of the liners. The method used was to cleanse the polymer surface with a gentle stream of deionized water for five minutes. No physical contact of the surface with any abrasive material, such as brushes or lint-free tissues, was attempted. This method did remove some of the crystalline material, but the crystals were not sufficiently water soluble to be completely removed. Although the crystals appeared throughout the surfaces of the polymers, the original surface texture was retained in terms of smoothness and structure.

Another problem arose during sample coating for SEM observation. Normally, a layer of gold-palladium is used to coat the surface. This coating is applied under high vacuum conditions. After the polymer surfaces were coated and brought back to atmospheric conditions, they underwent expansion which caused flaking of the coating in some cases and ripping of the coating in others. Several other coatings were tried, and aluminum was found to be the most suitable.

10.1.3 Total Organic Carbon Concentration

Samples of the leachate from each liner/leachate tank were analyzed in duplicate monthly for TOC using a Dohrmann Model 52/D TOC analyzer. This instrument employs a flame ionization structure to provide linear response up to 10 mg/L carbon concentration. After the TOC concentrations were obtained, they were normalized on both a mass basis (mg of TOC per g of liner) and an area basis (mg of TOC per in^2 of liner). The most significant value is the normalized value on a mass basis, so that value is reported and used for interpretation.

10.2 Neoprene Compatibility

Neoprene is a chlorine-bearing synthetic rubber which is generally very resistant to chemical attack by oil, to weathering, to exposure to ozone, and to ultraviolet radiation. It is very similar to natural rubber in its flexibility and strength, and it is resistant to puncture or mechanical damage. The samples used for this program had a thickness of 0.063 in. The surfaces had a screen-like grid with high square ridges and lower square interior areas.

The initial tensile strength of the neoprene prior to exposure to the Exxon PFBC waste leachate was about 1420 psi. This strength gradually reduced during exposure to the leachate until at 18 months the strength was about 900 psi (60% of the initial strength).

Before exposure to the PFBC leachate, the neoprene surface was found under SEM observation to have the screen-like grid described above. Both the ridges and the interior areas were found to consist of large flat plates. After 16 months of immersion in the leachates, the plates were largely obscured by the white precipitate that formed on the polymer surface. Where visible, the plates had not undergone significant erosion or breakdown.

On a mass basis, the TOC in the leachate containing the neoprene strips increased from 0.023 mg/g at the end of the first month of the experiment to 0.34 mg/g at the conclusion.

10.3 Polyvinyl Chloride Compatibility

Polyvinyl chloride (PVC) has been the most frequently used liner in existing landfill facilities where synthetic liners are used. Its popularity is probably linked to its resistance to petroleum products. Unfortunately, the plasticizers used to give PVC its flexibility have been shown to be biodegradable and partially water soluble. PVC also has the disadvantage of stiffening at low temperatures; however, it is quite puncture-resistant and easy to splice. The samples acquired for this investigation had a thickness of 0.032 in.

The tensile strength of the PVC liner had an initially lower value (1630 psi), then increased to 2090 psi, and subsequently decreased to a low of 1300 psi, about 60% of the maximum value observed.

The surface of the PVC liner was observed to be relatively smooth and homogeneous with a few shallow linear grooves. After 16 months of immersion, the liner surface had an etched appearance at low magnification, but higher magnification showed that the surface was completely encrusted with the crystalline material. The shallow grooves stimulated oriented crystal growth during the crystallization process. No evidence of liner breakdown was observed, although any effects would probably have been masked by the precipitate.

The TOC content of the leachate containing the PVC strips increased from about 1 mg/g at the end of the first month to about 4 mg/g at the end of the eighteenth month of the test.

10.4 Chlorinated Polyethylene Compatibility

Chlorinated polyethylene (CPE) is a completely saturated polymer, and its lack of double bonds makes it ozone-resistant. CPE resists cracking at low temperatures and is known for its good tensile strength. Its major disadvantage is its susceptibility to chemical attack by acids, caustics, and oils. The samples used were 0.030 in. in thickness. The polymer may have had fiber reinforcement materials added.

The tensile strength of the CPE was initially about 1430 psi. The strength increased to a maximum of 1670 psi in the third and fourth months of the experiment and then decreased gradually to 870 psi at the end of the final month, which is about 50% of the highest strength value noted.

The CPE samples had a slightly degraded or oxidized appearance when obtained from the vendor. Under SEM observation, the liner surface was quite rough and had long tubular "bumps" probably resulting from fiber reinforcement material. The strips that were exposed to leachate for 16 months were encrusted with precipitate from the leachate, but there were cracks in this coating through which the liner had a pitted appearance. CPE showed the strongest signs of liner surface deterioration after exposure to the leachate.

On a mass basis, the TOC content of the leachate increased from 0.75 mg/g after the first month of the test to 10.2 mg/g after 18 months.

10.5 Chlorosulfonated Polyethylene Compatibility

Chlorosulfonated polyethylene (Hypalon) is a synthetic rubber. It is puncture-resistant and performs well over a broad temperature range. It is not susceptible to attack by weathering, aging, oil, bacteria, caustics, or acids. Although this material is widely used, it is quite expensive. The samples used were 0.046 in. thick and contained reinforcement fibers.

Hypalon had relatively high initial tensile strength (about 2170 psi) which was maintained through the thirteenth month of the study. Thereafter, the strength decreased irregularly to a low of 1590 psi at the conclusion of the test, which is about 70% of the highest strength value noted.

Before immersion in the PFBC leachate, Hypalon had a relatively smooth appearance under low magnification of the SEM, although some indentations and linear features were seen. After 16 months of immersion, the surface had a much rougher appearance. The original indentations and linear features were deeper, and the surface had the appearance of "melting away". Thus, there was considerable evidence of surface deterioration resulting from exposure to the leachate.

The TOC concentration in the leachate used for immersion of the Hypalon liner strips was 0.71 mg/g after the first month and increased to 10.0 mg/g after 18 months.

10.6 Butyl Rubber Compatibility

Butyl rubber is a copolymer of isobutylene (97%) and isoprene. The major advantage of butyl rubber is its ability to resist permeation and swelling in water. It is, however, susceptible to ozone deterioration and chemical attack by hydrocarbons. Splices of butyl rubber also require the use of cold-curing adhesives, which is a difficult process. The samples acquired were 0.057 in. thick and were fiber-reinforced.

After the first month of the study, butyl rubber had a tensile strength of 1350 psi. This strength increased to a maximum of 1630 psi at the end of the fifth month and then decreased suddenly to 1120 psi at the end of the eighth month. The strength then remained relatively constant at about 1100 psi through the end of the tests. This final value was thus about 65% of the maximum strength observed.

The surface of the butyl rubber was apparently not significantly affected by exposure to the PFBC leachate. At low magnification, the surface consisted of large flakes oriented in a flat, sandwich fashion. After the 16 months of immersion, discrete platelets were still visible, but they were completely encrusted with the crystalline precipitate material. The liner surface itself was completely obstructed from view by the precipitate layer.

The TOC content of the leachate used for the immersion increased from 0.21 mg/g after one month of operation to 3.7 mg/g after the full 18 months of the experiment.

10.7 Ethylene Propylene Diene Monomer Rubber Compatibility

Ethylene propylene diene monomer (EPDM) rubber is also a synthetic rubber. Like butyl rubber, EPDM rubber is resistant to permeation and swelling in water. Unlike butyl rubber, it resists ozone attack, aging, weathering and most chemical attack. This difference is a result of the unsaturation in the side chain rather than the main chain, while the diene monomer introduces double bond sites for vulcanization of the rubber. EPDM rubber is not resistant to petroleum solvents or to aromatic or halogenated solvents. The samples used were 0.065 in. thick.

The tensile strength of the EPDM rubber liner was at least 1540 psi after the first month and remained near that level through the seventh month of the study. The strength then dropped to about 1200 psi until the fifteenth month. During the last three months, the strength was about 1100 psi, about 70% of the initial value.

The surface of the EPDM rubber sample was not greatly affected by exposure to the PFBC leachate. Before immersion, the surface had a relatively flat, smooth appearance consisting of small, closely bound platelates. The only difference in the appearance of samples that had been immersed in the leachate for 16 months was a complete encrustation with the precipitate which precluded direct viewing of the polymer surface.

The EPDM rubber leachate solution had a TOC content of 0.13 mg/g after the first month and increased to 0.64 mg/g after 18 months.

10.8 Comparison of the Compatibilities of the Synthetic Liners

Although the liner materials vary in thickness from 0.030 in. to 0.065 in. (more than two-fold), the results of the tensile strength test can be compared directly since the strength is defined in terms of stress rather than force at the point of failure. The results of the tests are shown for all the liners in Figure 10-2. Clearly, the Hypalon was the strongest of the liners tested overall. Four of the six liners (EPDM rubber, butyl rubber, neoprene, and CPE) have very similar strength properties. PVC showed strengths about midway between Hypalon and the other four liners.

All of the liners showed a decrease in strength with increasing time of exposure to the leachate. Expressed in terms of percentage of the maximum tensile strength observed, the greatest drop in strength was observed for CPE, with a decrease to 50% of maximum. The least decrease in strength was seen for the Hypalon and EPDM rubber liners (70% of maximum). The rate of decrease was quite similar for the four lowest-strength liners, except that CPE lost strength slightly more rapidly than the others. Hypalon appeared to lose strength at the lowest rate.

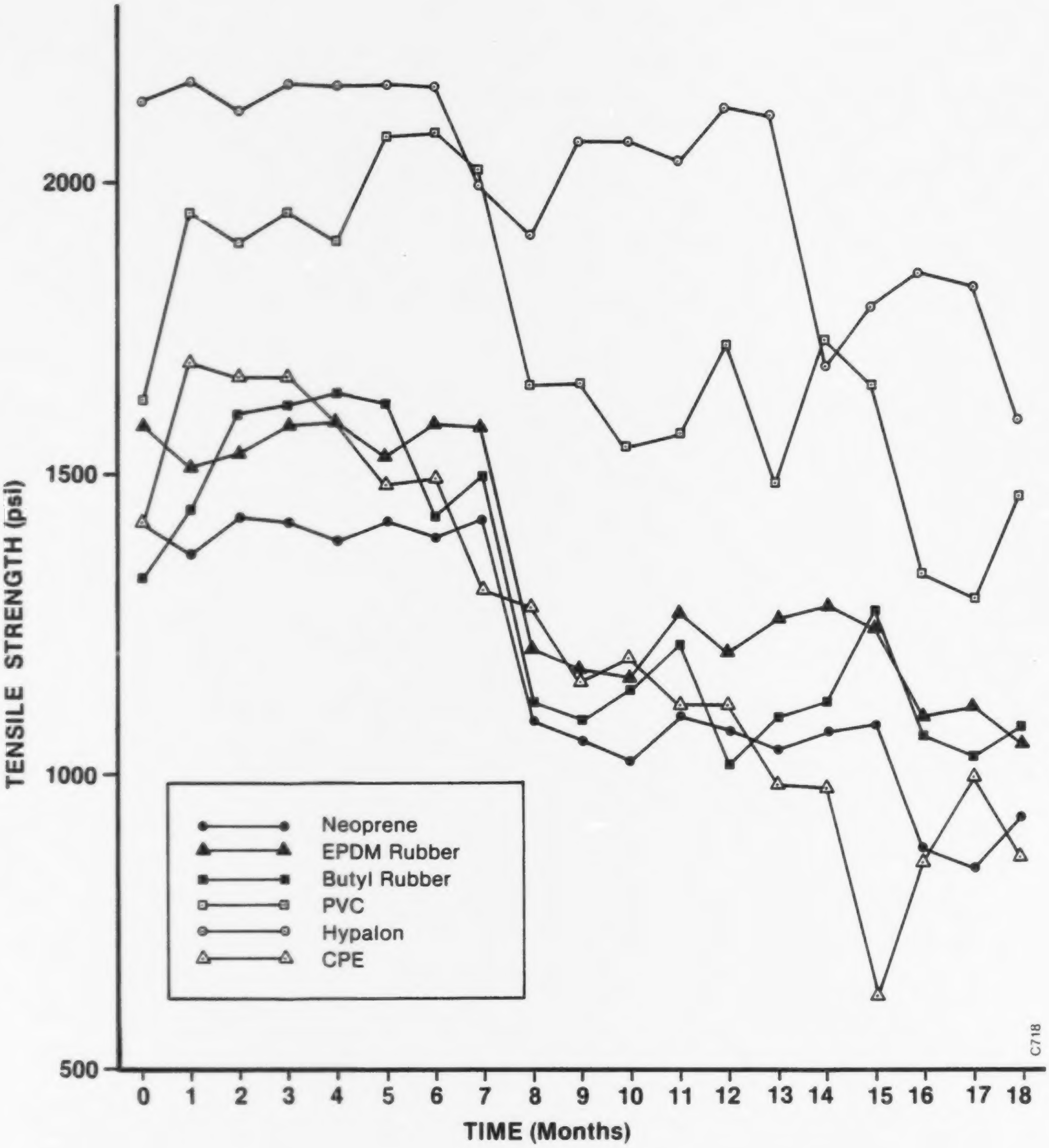

Figure 10-2. Tensile Strength of Candidate Liners as a Function of Exposure Time to FBC Waste Leachate.

Of the six liner materials observed under SEM magnification, only two (Hypalon and CPE) showed evidence of significant deterioration resulting from exposure to the Exxon PFBC waste leachate. The only effect shown by the other four liners was an encrustation by the crystalline material which precipitated from the leachate. It is possible that there may have been some effect on these liners, but the effect was masked by the precipitate coating.

The concentration of TOC in the leachates and the trend of this content over the life of the experiment are summarized in Figure 10-3. Hypalon and CPE showed both the greatest loss of TOC and the greatest rate of loss during the timeframe of the experiment. The leachates for both of these liners had a relatively high TOC concentration after the first month, and both showed a 14-fold increase during the ensuing 17 months. EPDM rubber and Neoprene both had the lowest TOC content and the lowest rate of loss. Both had TOC contents of less than 1 mg/g at the conclusion of the experiment. The other two liners (PVC and butyl rubber) showed TOC losses to the leachate and rates of loss intermediate between the high-loss liners (Hypalon and CPE) and the low-loss liners (EPDM rubber and Neoprene).

The results of the tensile strength determinations, SEM observations, and TOC content studies were generally consistent with each other. The liner showing the least compatibility was CPE; it showed the clearest sign of chemical degradation under SEM observation and by the TOC analysis. Its tensile strength was in the group of four liners having the lowest strength, and the rate of decrease of strength with increasing time of immersion was the greatest for all the liners.

Hypalon, on the other hand, showed signs of chemical degradation in the SEM and TOC studies, but its strength (which was initially high) remained the highest of the liners for the duration of the experiment.

PVC was found to be second only to Hypalon in strength, and it showed no signs of deterioration under SEM observation. Loss of TOC to the leachate was intermediate among the liners studied. Butyl rubber was similar to

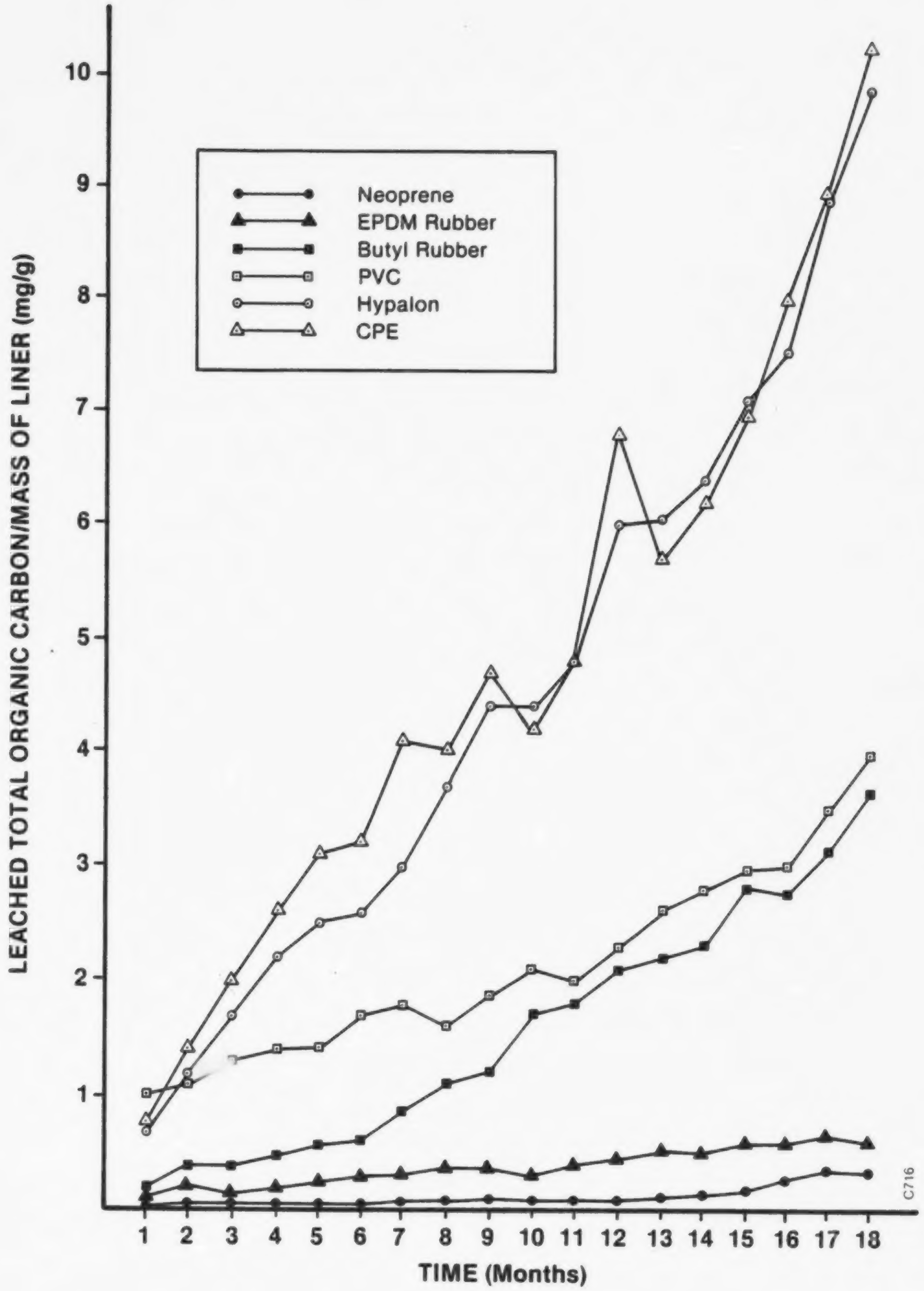

Figure 10-3. Leachable Total Organic Carbon (Mass Basis) from Candidate Liner Materials as a Function of Time.

PVC in the loss of TOC but was significantly lower in strength. No breakdown was observed by SEM observation. EPDM rubber had a very low loss of TOC, but was among the set of four weakest liners. Again, no deterioration was seen with the SEM. Neoprene lost the least TOC to the leachate, but was again among the four weakest liners. No breakdown was seen under the SEM.

10.9 Procedures for the Clay Liner Study

The clay liner material used in the experiments was a sodium-exchanged Wyoming bentonite. This clay was placed in continuous and intimate contact with the Exxon PFBC waste leachate. The following observations were made monthly to assess possible clay lattice degradation:

- Crystalline structure by X-ray powder diffraction (XRD);
- Particle morphology and composition by SEM and X-ray fluorescence (XRF); and
- Aluminum concentration in the leachate.

The XRD and SEM observation allowed direct observation of changes in the clay minerals and their structure, whereas an increase in aluminum concentration in the leachate was used to indicate if chemical breakdown of the clay lattice by the leachate was occurring.

A suspension with a 10:1 leachate-to-clay ratio was shaken continuously in a batch equilibration procedure. At the end of each month, a uniform aliquot of 50 mL was removed and centrifuged. The liquid from the centrifuged sample was decanted for aluminum analysis, and the solids were dried in an oven at 40°C. The oven-dried samples were stored in air-tight vials until they were analyzed by XRD and SEM.

10.9.1 X-ray Diffraction Analysis

The XRD analyses were performed at Baylor University, Waco, Texas. The samples were analyzed using a Philips X-ray diffractometer and a special holder designed for use with small samples. Prior to analysis, the samples were brought to equilibrium in a 51% relative humidity dessicator. Just before analysis, the diffractometer was flushed with air at 51% relative humidity. Each diffraction analysis was performed in duplicate. Six of the samples generated during the experiment were subjected to XRD analysis, including an unleached sample and the 1-, 3-, 7-, 13-, and 18-month samples from the immersion test.

10.9.2 Scanning Electron Microscopy and X-Ray Fluorescence

The same instrument used for the polymer liner investigation was used for the clay examination, but the clay samples were prepared differently. The powdered samples were secured on the discs in the same manner, but a standard gold-palladium alloy was used as the coating. Each sample was examined by the SEM at two magnifications (500X and 5000X). In addition, XRF scans were produced for elemental analysis of selected portions of individual particles.

10.9.3 Aluminum Concentration in the Leachate

The aluminum concentrations in the leachate were measured by ICAPES, whose detection limit for aluminum is superior to atomic absorption spectrophotometry (AAS) methods. Each sample was analyzed three times by ICAPES.

10.10 Clay Liner Compatibility

The leachate used for the bentonite clay liner study was again Step 1, 7-day leachate from lab protocol leaching of Exxon PFBC wastes.

10.10.1 X-Ray Diffraction Results

The clay sample was analyzed before exposure to the leachate and was found to be composed of sodium montmorillonite and some quartz. Five of the samples taken during the batch immersion were tested by the XRD method. One of the first changes observed was the alteration from a sodium- to a calcium-montmorillonite as the calcium in the PFBC leachate replaced the sodium ions in the interlayer positions of the montmorillonite.

After the first month of exposure to the PFBC leachate, a new mineral, ettringite ($Ca_{12}Al_3(SO_4,SiO_3,CO_3)_6(OH)_{21}\cdot30H_2O$), was identified from the XRD patterns. There was a gradual increase in this mineral through the experiment. It is likely that this mineral formed by reaction of the montmorillonite with the leachate.

Although one of the peaks on the XRD pattern changed slightly as the experiment progressed, which may have been an indication of incipient breakdown of the aluminosilicate structure of the clay, the patterns in general showed no major structural change in the clay. Only the formation of the new mineral phase, ettringite, indicated a change in the basic structure of the initial clay minerals.

10.10.2 Scanning Electron Microscope and X-Ray Fluorescence Results

Samples of the bentonite clay prior to exposure to the PFBC leachate were observed by both SEM and XRF. Two distinctly different clay mineral morphologies were observed -- a "rosette" structure typical of montmorillonite and a blocky structure. XRF analysis showed that the rosettes had less aluminum and more magnesium than the particles with the blocky structure. Both particle types showed the presence of sodium but not calcium.

After the first month of exposure to the PFBC leachate, the overall rosette pattern of the montomorillonite appeared to be substantially unchanged. However, when XRF scan was made of one of the rosettes, the composition was found to be greatly changed. Almost all of the sodium was gone, and a prominent calcium peak was observed. The aluminum-to-silicon-to-calcium ratio was from 1:4:2 to 1:4:4, and a sulfur peak was observed. Newly developed crystallites were also observed and were subjected to XRF analysis. This analysis showed an aluminum-to-silicon-to-calcium ratio of 1:3:1 and indicated the presence of calcium sulfate or, most likely, a complex mineral containing calcium, silicon, and sulfur (such as ettringite).

After three months of exposure, the clay samples showed little change from the one-month sample, except that a new crystallite with an Al:Si:Ca ratio of 1:3:13 was observed. This calcium compound was probably a precipitate from the leachate. No major additional changes were observed in the seven-month sample. An XRF scan of one of the montmorillonite rosettes had an Al:Si:Ca ratio of 1:9:3.

Again, after 13 months of leachate interaction, there was little change noted in the appearance and composition of the clay and the new crystalline components. XRF spectra showed that the clay rosettes were calcium-montmorillonite, and the crystallites had Al, Si, Ca, and S proportions consistent with ettringite. After 18 months, there was again no change except for the continued additional of ettringite and precipitation products from the leachate.

10.10.3 Aluminum Concentration in the Leachate

Throughout the experiment, duplicate analyses of the leachates for aluminum showed that the concentration was at or below the level found in the leachate before interaction with the clay. Thus, no chemical breakdown of the internal aluminosilicate structure was indicated over the 18 months of the test.

10.11 Summary

In general, the liner materials tested were found to be quite compatible with Exxon PFBC waste leachate insofar as could be determined in this relatively short and simple investigation. If there had been strong incompatibility of the liners with the leachate, then the degradation would have been readily detected in this program. Although no strong incompatibility was observed, some of the polymer liners did show a significant loss of tensile strength during the 18 months of leachate exposure. The formation of a new mineral phase, ettringite, as the probable reaction product of the montmorillonite and the high-calcium leachate could also lead to eventual breakdown of the effectiveness of the clay or a liner material. Additional study with a specific waste would be advisable before any of the liners are used at a future FBC waste disposal site.

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Conversion Table for English to Metric Units

1 foot = 0.305 m

1 inch = 2.54 cm

1 gallon = 3.785 L